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Erosion trends in the Minnamurra River catchment: An application of the RUSLE model

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Abstract

Erosion and sedimentation present a significant problem in catchments across the world. The Minnamurra River catchment prior to European colonisation was a well-vegetated landscape with established forests and swamplands. The area was cleared for timber and established as a dairy farming region in the early 1900s. As of 2015, 57.3% of the catchment is considered grazing pastureland. The aim of this study is to identify the erosion patterns of the Minnamurra River catchment and identify sub-basins that require management attention using a GIS modelling approach. The model selected was the Revised Universal Soil Loss Equation (RUSLE). This choice was based on the model's ability to address the two major classes of erosion, sheet and rill, as well its low data requirement and success in similar catchments. The model accounts for primary factors contributing to erosion without the need for extensive input parameters. These factors are rainfall, soil composition, land use and landscape topography.

The RUSLE hillslope erosion model calculated in the report uses a combination of four factors, rainfall intensity (R) and length slope factors (LS), determined using theoretical equations extracted from rain gauge data and digital elevation models (DEMs). In addition, two weighted nominal factors were determined from lookup tables which account for land use (C) and soil erodibility (K). Validation of the model was undertaken using field water sampling, model comparison and site inspections.

The results of modelling showed that the catchment is eroding at a mean rate of 0.82tons/ha/yr. More importantly, the RUSLE model revealed that areas of highest erosion occur on the cleared slopes of the northern and southern sections of the catchment, whereas the upper catchment is significantly protected from erosion by forest cover. RUSLE identifies broad scale erosion trends effectively but is limited when small-scale erosion occurs due to factors such as bank failures and poor riparian vegetation. Improvements to the model could include the addition of higher resolution input data for the R, C and K factors and a full coverage LiDAR program. Ongoing management in the catchment should focus on the improvement of hillslope and riparian vegetation in the Curramore, Rocklow, Jerrara, Fountaindale and Hyams sub-basins. With specific recommendations to address a sever bank erosion site in the Curramore basin and remediate the water quality in Fountaindale Creek.

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Erosion trends in the Minnamurra River catchment: An application of the RUSLE model

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Throughout my bachelor's degree at the University of Wollongong, the Honours thesis has always been a driving force behind my study. Having a goal to reach pulled me through when subjects got rough, but I always knew it would be worthwhile. I'm happy to say that at the end of this thesis, I feel as though it was worth the wait and the work.

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Abstract

Erosion and sedimentation present a significant problem in catchments across the world. The Minnamurra River catchment prior to European colonisation was a well-vegetated landscape with established forests and swamplands. The area was cleared for timber and established as a dairy farming region in the early 1900s. As of 2015, 57.3% of the catchment is considered grazing pastureland. The aim of this study is to identify the erosion patterns of the Minnamurra River catchment and identify sub-basins that require management attention using a GIS modelling approach. The model selected was the Revised Universal Soil Loss Equation (RUSLE). This choice was based on the model's ability to address the two major classes of erosion, sheet and rill, as well its low data requirement and success in similar catchments. The model accounts for primary factors contributing to erosion without the need for extensive input parameters. These factors are rainfall, soil composition, land use and landscape topography.

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1 Introduction

The Minnamurra river and its catchment provide a vital supply of water and sediment to the surrounding lands and estuary. Prior to European arrival the catchment was covered by cedar forest with a lower catchment swamp. The region was first recognised by the European settlers as a hub for logging. This led to early clearance of the catchment's vegetation. Following logging the region suffered extensive sediment losses as soil was exposed to the erosive effects of rainfall and subsequent runoff. This period was immediately followed by draining of the floodplain, cut-off of the main-stream and the establishment of a major dairy farming industry (Panayotou 2004). A broad scale erosion program has not been applied to assess the erosion trends that occur in this catchment and thus this knowledge gap with be addressed in this study.

1.1 Study site

The Minnamurra river is a stabilised rural catchment located 90km south of Sydney. The river and its estuary are the result of valley infill and sea level stabilisation (Panayotou 2004). The river is confined by the Great Dividing Range in the west and the sea in the east. From its headwaters above the escarpment at approximately 600m above sea level the river runs through Permian – Triassic sedimentary and igneous units, the majority of which fall under the 'Gerringong volcanics' group (Panayotou 2004). The catchment has a total area of 115km^2 and flows into a river dominated estuary fed by several significant tributaries. The tributaries in focus for this study are, Jerrara Creek, Fountaindale Creek, Colliers Creek, Hyams Creek, Fry's Creek, Burra Creek, Rocklow Creek and Turpentine Creek (Figure 1). These tributaries serve as water sources for local farms and thus need to be regulated to ensure that sediment and nutrient loads are kept under acceptable limits. The upper catchment has one major township, being Jamberoo and the lower reaches of the catchment flow through the townships of Kiama downs and Minnamurra.

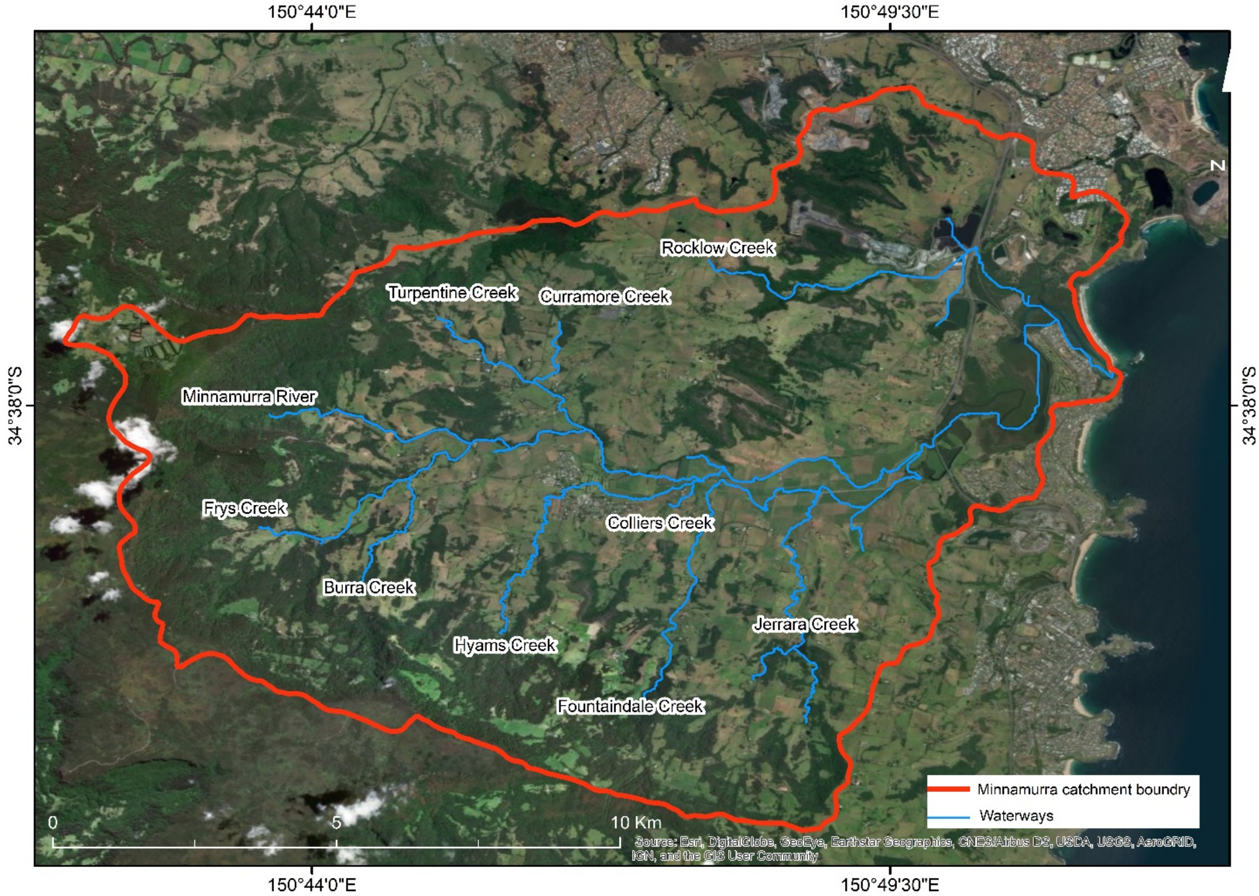

Figure 1 study site with water ways and tributary names

1.1.1 Catchment Evolution

A five stage Holocene evolution history has been generated for Minnamurra river/estuary using foraminiferal evidence (Haslett and Davies-Burrows, 2010). The catchment began as a central swampy basin between 8000-6500 yrs BP as the sea infiltrated the palaeovalley. Between 6500-4500 yrs BP, sea level rise slows and a barrier forms at the estuary mouth. 4500-2500 yrs BP further barrier development occurred aided by fluvial sediment from the greater catchment. 2500-100 yrs BP, confinement of the river channel and formation of a wide-ranging floodplain from a previous mud basin, possibly due to a tsunami event. 100 yrs BP, marks the beginning of European influence, the draining of the floodplain for agriculture and artificial straightening. In its current state the estuary exists as a river dominated mature barrier estuary (Roy et al., 2001). The Kiama/Minnamurra region first received European attention due to its abundance of red cedar trees, logging of the areas forests began in the 1820's (Bayley 1976). During the late 1800's-early 1900's much of the floodplain was drained and a lower section of the river was artificially straightened to accommodate for dairy farming (Oliver 2011). During this period of European settlement large amounts of sediment would have been washed down stream, settling on the lowland plain or deposited in the estuary, with these areas becoming major sediment sinks. The river incised as a result of the increased stream power after the stream was straightened. During the 1950's and mid 1970's the straightened segment of the river was de-snagged and enlarged laterally, as a result another period of channel incision occurred (Panayotou 2004). The paleo channels of the former river remain visible along the lower floodplain. The main channel running through the floodplain is approximately 5-10m and 3m deep with significant levee's (Panayotou 2004). The river also exhibits a pattern of declining width and cross-sectional area downstream up until the estuary region is reached. Nanson and Young (1981) identify this trend as the result of a reduction of slope and stream power and is the same pattern observed in Macquarie rivulet to the north Minnamurra river.

1.1.2 Current State

The Minnamurra River in its current form is a slowly adjusting meander river, with overbank sedimentation the predominant method of floodplain deposition (Nanson and Croke, 1992). Along the river swampy billabongs exist remnant of the former channel, these areas have now become very stable sediment sinks (Chafer 1998). Table 2 of the Coastal Zoning Management Plan (CZMP) for Minnamurra River (2015) outlines the broad land use classes along the Minnamurra river catchment. 57.3% of the catchment as of 2015 is used as grazing land, which consist of large expanses of grass land with minimal tree cover (Table 1). Along these sections riparian vegetation is present, however there are areas where this vegetation cover is significantly reduced, for example the mid reaches of Fountaindale Creek. Conserved forest areas comprise 27.4% of the catchment. These areas are predominantly located at the headwaters of the main river and its tributaries, other notable conservation areas occur in the back swamp of the estuary. The 7.2% urban development occurs in the Jamberoo, Kiama Downs and Minnamurra townships. These areas are considered low-medium density suburbs, with limited scope for future expansion. It is also worthy to note that the river runs parallel to Jamberoo golf course for up to 700m (Google Earth path map). The river itself has become a well-developed floodplain with a small - intermediate agriculture industry that effectively attenuates flood waters as they move down the floodplain (Panayotou 2004).

Table 1: Table 2 of the Minnamurra river CZMP based on 2014 CERAT mapping by the OEH

Type	Description of land use category	Area (ha)	% of total catchment
Cleared	Cleared land, production forestry, dryland agriculture and plantations, intensive animal production, mining, waste treatment and disposal	140	1.2%
Conservation	Forest, nature conservation	539	4.6%
DryForb	Perennial and seasonal horticulture	5	0.0%
Grazing	Grazing land	6,719	57.3%
Irrig5	Irrigated modified pastures and cropping	32	0.3%
IrrTree5	Irrigated perennial horticulture	15	0.1%
River	Estuary/coastal waters	89	0.8%
Sand	Estuary/coastal sand	0	0.0%
Scrub	Nature conservation, native vegetation, grazing with natural vegetation	3,211	27.4%
TreeHort	Plantation forestry, cropping, perennial horticulture	2	0.0%
Urban	Urban land including rural residential areas	843	7.2%
Wetland	Marsh/wetland	124	1.1%
TOTAL		**11,719**	**100%**

1.2 Rationale for this study

Management plans that account for the Minnamurra River catchment have been predominantly focused on the lower estuary section of the basin. As such the processes that occur in the upper sections of the catchment has been neglected and needs to be addressed. In this way it is justifiable to state that a study of upper catchment processes is vital to understanding the processes occurring in the lower section of the catchment. This report provides a preliminary answer to the question, 'what are the erosion and sedimentation processes that occur in the upper Minnamurra River'.

Using GIS based modelling methods aided by field collection and sample analysis will contribute to my skill development in resource science. By undertaking this research project, I am developing a specialised understanding of the upper Minnamurra river, and this knowledge could be applied in similar regions such as the Bega valley and Shoalhaven river. It will also develop my understanding of GIS and its ability to represent real life environmental processes. The fieldwork and lab components will contribute to my growing professionalism in efficiency and reporting accuracy, which is an asset in this discipline.

1.3 Aims and Objectives

The aim of this study is to identify the erosion patterns of the upper Minnamurra River catchment and identify sub-basins that require management attention using a GIS modelling approach. This aim was achieved by undertaking the following objectives:

1. Review sedimentation literature to establish the concepts that drive erosion on the catchment scale
2. Review models and methods used to estimate sedimentation trends in catchments
3. Undertake a GIS based assessment of hillslope erosion using the Revised Universal Loss Equation (RUSLE)
4. Validate a GIS model through field and lab analysis, using water samples collected from the major tributaries of the Minnamurra river
5. Compare the results of this study to available data from the application of erosion and nutrient models created in Office of Environment and Heritage (OEH) studies
6. Present recommendations for further research using catchment scale models and management implications of the study

In this study the RUSLE model is applied to the Minnamurra River catchment, to assess its usefulness for catchment remediation and monitoring. It is anticipated that the RUSLE model and associated validation methods will identify the erosion trends occurring in the catchment and help to guide further research and located areas requiring management attention.

1.4 Thesis Outline

The thesis will act as a pilot study for further investigation into the sedimentation tends occurring in the Minnamurra River. The introduction has presented the setting of the Minnamurra River catchment and its historical evolution over time. Chapter 2 consists of a literature review, which will firstly focus on the driving factors of erosion in catchments and is followed by an analysis of models and methods that allow researchers to estimate how these factors interact in the landscape. In chapter 3 the methods used in the study will be outlined. There are two aspects to the methodology, the first is the GIS based desktop analysis with stipulates the expected observations and acts as the foundations of the study. Desktop modelling requires validation, and to do this field and lab work encompass the remainder of the methods. Chapter 4 is the collation of desktop, field and lab methods used, and provides adequate visual and statistical representations of data collected. Chapter 5 discusses the results observed in the previous chapter and attempts to link it to trends observed in the literature. The recommendations for Kiama Municipal Council (KMC) are also presented in chapter 5. In chapter 6 the study is concluded with some final remarks relating to the usefulness of RUSLE in catchment studies.

2. Literature Review

2.1 Soil Erosion

By developing an insight into soil erosion processes, we can predict and understand how sediment movements occur on a landscape. Soil loss is the main factor considered when talking about soil erosion, as it is an important resource, especially in agriculture, where loss of soil commonly results in a reduction of land fertility. Soil erosion itself, however, does not mean that it has been lost in the system, it can also be deposited, predominantly at the base of slopes and in waterways (Van Remortel, Maichle, and Hickey, 2004). Off-site impacts of soil erosion are also important, these occur when sedimentation in occurs waterways disturbing water flows, streams and reservoirs, for example through increased turbidity or nutrient loading from fertilised farm pastures and cropland, which can damage aquatic ecosystems (Collins and Owens, 2006). There are three broad forms of soil erosion that occur in catchments; sheet, rill and gully, and these are influenced by catchment specific factors such as rainfall, topography, soil structure, land cover, and land use practices.

2.1.1 Soil Detachment

During a rainfall event, water droplets interact with the ground, and can result in a rain splash effect that mobilises sediments. This is the result of a kinetic energy release after a water drop falls on a bare or semi bare section of sediment, causing the physical and chemical detachment of particles (Knighton 1998). The magnitude of this action depends on the intensity of the precipitation, and the structure of the soil in terms of moisture content, organics content, clay percentage, etc, and topographic features such as slope angle and slope length. The potential for soil to erode is termed soil erodibility (Lal and Elliot 1994). Following soil detachment soil is transported by overland flows as inter-rill erosion (sheet erosion) and in concentrated flows by rill erosion (Lal and Elliot 1994)

2.1.2 Sheet Erosion

Sheet erosion is the result of soil detachment and the subsequent mobilisation of sediments in shallow overland flows (Lal and Elliot 1994). An overland flow event will occur when the maximum infiltration of a substrate is reached, forcing water to flow on top of the surface, carrying surface sediments with it (Knighton 1998). Therefore, the extent of sheet erosion is predominantly dependant on the soil structure and land cover, determining permeability (Knighton 1998). For example, a pastureland covered on with scattered trees, grass and livestock affected compacted soil will exhibit overland flow more immediately and for a longer duration than a forested area of similar soil composition, as the infiltration rates are much higher in the forest. Sheet flows are not uniform, rather they consist of irregular movements of water, both in shallow slower flows and slightly deeper fast flows. On flat or gentle slopes, the main driver of soil detachment is raindrops, and overland flow only acts as transport, however on steeper slopes overland flow can produce velocities great enough to drive detachment itself, making steeper slopes more vulnerable to erosion (Knighton 1998).

2.1.3 Rill Erosion

Rill erosion occurs when an overland flow reaches a confined area of flow, when this happens the flow is directed and velocity increases. Water and sediments are carried down micro channels that have typical dimensions of 50-300mm wide and 300mm deep (Knighton 1998). Unlike sheet erosion, rill erosion will not occur on a flat landscape and requires slopes of at least 2-3^{o} to occur. At lower slopes the downwards energy of water flow is not strong enough to form channels. In rills the erosive energy is greatly increased in comparison to sheet flows, as a result rill erosion is a greater driver of erosion than the latter, contributing to 50-90 percent of erosion occurring in a typical catchment (Knighton 1998)

2.1.4 Gully Erosion

Gullies are features of extreme and focused erosion, and once developed they can become permanent features of a watercourse. When gullies occur, they are often considered as indicators of sudden accelerated erosion. Such erosion increases may be attributed to land use change, such as fire, forest clearance and overstocking (Knighton 1998). Gully erosion occurs on slopes greater than 12-16^{o} (Knighton 1998). Left unmanaged the gully will increase in size, as runoff causes the initial head cut to continue retreating. Unlike sheet and rill erosion, gully erosion is highly variable depending on specific catchment conditions, in many cases gully erosion is only a minor contributor to erosion where in an alternate catchment it may be one of the major drivers of erosion (Knighton 1998). Therefore, it is vital to identify whether the catchment is heavily affected by gullies, as many models do not account for them.

2.2 Climate and landscape factors contributing to sedimentation

The effects of climate are highly variable throughout the world, therefore, to determine the effects of climate, region-based analysis is required. Climate effects the rainfall and vegetation cover of a catchment, and there is no simple relationship between the two as rainfall increases sediment yield and vegetation reduces sediment loss (Charlton 2008). Topography however may be an easier factor to characterise, as it is unchanging in comparison (Charlton 2008).

2.2.1 Rainfall

Rainfall erosivity is the quantified kinetic energy of rain splash and sheet wash (Yang and Yu 2015). The effects of rainfall on a bare surface is considered the rain splash and is the driver of soil detachment. Rainfall intensity is more important than rainfall duration or volume when considering the erosivity of a rainfall event (Simms 2007). When rainfall intensity is high, there are greater forces acting on sediments forcing them to move, and depending on storm duration, greater intensity events lead to rapid surface flow formation (Van Dijk et al., 2002). Large raindrops also tend to contribute to higher erosion rates, due to the greater terminal velocity reached and the greater volume of water released (Van Dijk et al., 2002).

Runoff generation is the secondary driver of sedimentation as a result of rainfall. It occurs in two main states, Hortonian overland flow and Saturated overland flow. Hortonian overland flow occurs when the intensity of rain exceeds the natural infiltration rates of the soil or surface. This commonly occurs at greatest intensity in trampled pastures and in urban areas, and results in rapid runoff that can remove vast amounts of sediment (Simms 2007). Saturated overland flow occurs in lands where subsoils are saturated and rise to the surface during rain. This appears in areas close to waterways or wetlands and occurs due to total rain volume rather than intensity (Simms 2007). It is suggested that rainfall events occurring in short succession may compound with increased erosion, as the landscape remains in a vulnerable state with saturated soils and exposed features such as fresh gullies (Simms 2007). These events may become more common under the influence of climate change.

2.2.2 Topography, Lithology and Soils

Topography plays an instrumental role in the amount of energy transfer during rainfall as well as directing flows throughout basins. It is one of the most important factors in the determination of catchment erosion and is the combination of slope steepness and slope length. In areas with steep slopes such as mountain ranges, the amount of downwards energy enhances the effects of rainfall and surface flow (Charlton 2008). The length of a slope also influences sedimentation, as overland flows cover a greater distance at sustained velocities. The length of slope can also determine the development of erosional forms, for example a slope of 10m will exhibit sheet erosion only, where a longer slope of 46m will allow for the development of rills (Bryan 1979, 2001; as cited in Simms 2007). In general, however, the steepness of the slope is said to account for most erosion for any given topographical feature (Yang 2015). On short and steep slopes, the effects of rainfall are the most extreme. In these cases, soil detachment occurs rapidly, and the sediment carried in the resulting flows do not slow down and deposit until they have reached a waterway. As a result, rugged landscapes, such as alpine regions contribute a higher sediment load to their tributaries than more undulating landscapes (Simms 2007).

The geology of a region in part, determines the soils that occur, the composition of these soils determine the potential erodibility of the land. In arid regions sandy soils are common and are readily eroded by wind (Eldridge and Leys 2003). In temperate and subtropical regions such as the Minnamurra catchment, soils are more cohesive, due to higher silt, clay and organics content, and are rarely moved without water. The cohesiveness and shear strength of a soil determines the level of sheet, rill and gully erosion that will occur (Merrit, Lechter and Jakeman 2003). Other binding agents such as organic substances like mucilage and mycelium can also increase the shear strength of a soil (Simms 2007).

2.2.3 Land use and Vegetation Cover

Land use and vegetation account for erosion protection. Vegetation creates a form of soil armouring by preventing direct rain splash, increasing water infiltration, increasing landscape roughness, providing a foundation for soil cohesion and contributing to soil permeability (Simms 2007). The level of natural vegetation is controlled by climate, soil fertility and human interactions. Humans have been altering landscapes for thousands of years, but these actions have accelerated rapidly since the industrial revolution. Human activities that increase erosion include deforestation, agriculture, and mining (Charlton 2008). These activities remove the protection provided by native vegetation and expose sediments, they also alter water regimes and can lead to more extreme forms of sediment loss such as gullying. Human structures also can increase the rate of runoff during storms, as many of these features are impermeable such as roads and pathways. Anthropogenic vegetation categories such as pastures are vulnerable to mass failure due to a lack of root structure holding soil together, they also do not provide the same level of surface resistance as natural vegetation landscapes and thus do not provide much resistance to surface flows (Simms 2007).

2.3 Pressures and Risks to the upper catchment

In 2010 the Minnamurra river was included in the NSW *State of Catchments* (SoC) 2010 report (Roper et al., 2011). The report concluded that the Minnamurra river estuary is in a moderate state of ecosystem pressure. The catchment does not encounter heavy extraction of water or receive heavy runoff, it is also well regulated by the tides due to the open river mouth, estuary vegetation is mostly intact and fishing pressures are low. (Roper et al., 2011). The SoC report highlights that the Minnamurra river is under high pressure in terms of cleared land (66% of the total catchment area is cleared), and population pressure. The main findings of the SoC report that are relevant for this thesis are an observed 531% increase in annual total suspended solids (TSS), a 568% increase in annual total phosphorus (TP) and a 158% increase of annual total nitrogen (TN) input when compared to a natural state. The lower estuary is constantly flushed, and this maintains a stable nutrient balance, however mid and upper river reaches have exceeded ANZECC water quality conditions on a semi regular basis (Hydrosphere Consulting 2015).

The Coastal Eutrophication Risk Assessment Tool (CERAT) is used in the 2015 Kiama Municipal Council Coastal Zone Management plan as a basic reference to model simulations of catchment factors (Hydrosphere Consulting 2015). The CERAT models showed that irrigated cropland, intensive agriculture and cleared sites contribute the highest loads of sediment and nutrients to the catchment. The models show that general grazing areas and towns such as Minnamurra and Jamberoo contribute a moderate amount the sediment and nutrients. Lowland grazing/ pasture however such as those along swamp road contribute a low amount of sediment and nutrients. The upland bush and rainforest land also contribute a minor amount of sediment and nutrients to the catchment. In agricultural catchments the effects of land clearance increase the incidence of rainfall driven sheet and rill erosion as well as contributes to soil stability erosion such as gully erosion and bank slump (Radke et al., 2004).

2.3.1 Possible impacts under Sea Level Rise

Sea level rise as a result of climate change is expected to affect the Minnamurra river and estuary in the coming years. Projections from coastalrisk.com.au show that highest tides by the year 2100 will be 0.74m deeper, inundating extended areas to the north via Rocklow Creek, and west via the main river and Jerrara Creek. As a result, we will likely see an extension of salinity affected areas and possible erosion increases due to the increase volumes of water running in and out of the river.

Losses to riverbank vegetation could occur as water levels rise, forcing the relocation of ecological communities (Hydrosphere Consulting 2015). When this occurs in areas restricted by manmade infrastructure, vegetation loss can occur. Mangroves function as significant stores of carbon, therefore their health is of value to climate mitigation, losses of these communities by possible sea level rise drowning and coastal squeeze on a global scale could have the extended effect of accelerating the effects of climate change (Woodroffe et al., 2016). Estuaries low in sediment accumulation are at the greatest risk of SLR drowning, with little vertical accretion occurring from river-based sediments the mangroves rely on to build their root structures (Woodroffe et al., 2016 p. 254).

Accommodation space refers to the areas within the tidal limit that can act as depositional stores of sediment, mangroves are central to this process. Under sea level rise, sediment accommodation space may move inland and reflect the movement of vegetation communities. In addition, this may free up in channel sediment that was once held in place by the former biological bank structure. (Woodroffe et al., 2016 p. 251)

2.4 Modelling Sedimentation Changes at the Catchment scale

To determine the amount of changes occurring in a catchment, scientists create factors that represent real world processes (Wilkinson et al., 2013). Traditional methods of estimation sedimentation tend to include, estimation of accumulation rates in downstream lakes, sediment cores and radiometric dating (Simms, Woodroffe and Jones 2003). Therefore, using a geospatial model is a much more efficient and cost-effective way to estimate the amount of erosion occurring on a catchment scale. It is however noted by Simms (2007) that most models only include two of the three main soil loss processes (sheet, rill and gully) in their calculations. Therefore, to create a complete picture of catchment scale processes one complex model or multiple simple models can be used, this is dependent on data availability, data quality and project timelines (Simms 2007). There are three major classes of models, Empirical, Conceptual and Physics based (Merritt et al., 2003).

Empirical models are the simplest of the three and require the least amount of data. While they are comparatively simple, they do provide rapid assessments of environmental trends without the requirement of extensive field study, as most inputs will be readily available in open access databases (Merritt et al, 2003). Limitations to empirical models include their tendency to consider processes as homogenous and limited capacity to provide event-based predictions (Merritt et al.,2003). It has been shown that these limits can be altered, such as in the event based MUSLE by Simms (2007). Conceptual models exist in the middle ground between empirical and Physics models, and in this way conceptual models are based on representations of internal processes occurring in catchments (Merritt et al., 2003). They run using pre-existing concepts on expected behaviours of factors such as sediment transport or riparian vegetation interactions but are not based on 'known' variables. Therefore, these models require extensive calibration with field data and are prone to overcomplication (Merritt et al., 2003). Physics based model are the most complex of the three model groups and require the most complex input parameters. When used correctly they function as a close representation of spatially heterogenous environmental processes (Merritt et al., 2003). They are specialised models that require site-based calibrations due to their high-resolution reporting, thus they require much more time to compute and execute correctly (Merritt et al., 2003).

2.5 Review of catchment scale sedimentation models

USLE, and RUSLE

The Universal Soil Loss Equation (USLE) is a model developed by the US Department of Agriculture in the 1960-70s for the application of predicting soil loss in agricultural areas (Simms 2007). USLE in its unmodified form in a linear model and was designed to make soil loss estimates on the plot scale (Wischmeier and Smith, 1978). In this form it was used extensively in the USA and worldwide and is generally considered to produced accurate assessments of annual soil loss. The USLE uses five basic factors contributing to erosion to calculated annual losses. These factors are, soil erodibility (K), the length and steepness of slopes (LS), land cover and management (C), rainfall erosivity (R), and any practices put into place to limit the effects of erosion (P).

The Revised Universal Soil Loss Equation (RUSLE) is as the name states, is a revision of the original USLE. Renard et al., (1991) developed the model to refine the soil loss equation by considering a broader range of parameters, which had not been studied in the USLE. Some notable improvements include a revised slope calculation, a new subfactor method for estimating cover management and improvements in the definition of the soil erodibility methodology (Renard et al., 1991).

The USLE and its derivatives use the following equation for hillslope erosion:

$$A = RKLSCP$$

Rainfall Erosivity Factor (R)

Rainfall erosivity is measured as the amount of kinetic energy occurring as a result of rainfall intensity. RUSLE considers this factor in terms of the maximum 30-minute intensity (EI_{30}) and is measured in MJ.mm / (ha.h.yr) (Simms 2007). Rain splash is the main driver of erosion in terms of rainfall erosivity in the RUSLE model, effectively beginning the mobilisation of particles (Ganasri and Ramesh, 2015). This erosivity drives the processes of sheet and rill erosion which transport sediment during water flows (Renard et al., 1991). The R factor is heavily modified depending on the orographic and climatic features of each region. the base formula as described in the original USLE (Wischmier and Smith, 1978), is presented as follows:

$$R = \frac{1}{n}\sum_{i=1}^{j}(EI_{30})_i$$

R = rainfall erosivity factor (MJ mm h-1ha-1yr-1), n = total number of years, j = total number of storms, I_{30} = maximum 30-minute intensity (mm hr-1), E = total kinetic energy (MJ ha-1) of jth storm of ith year

Length Slope Factor (LS)

The USLE slope length factor is a combination of the Slope length (L) and the slope steepness (S). This factor is a representation of the erosive susceptibility of topography. The slope length accounts for the length of significant slope for a section of land, while the slope steepness accounts for the angle of the hillside (Renard and Ferreira 1993). Within the LS factor, the slope steepness is the stronger component in the determination of soil loss in comparison to slope length (Renard and Ferreira 1993). This factor requires elevation data and is most commonly calculated using Digital Elevation Model (DEM) data (Shen, Yang and Zhu 2019)

Soil Erodibility Factor (K)

The K factor represents the intrinsic erodibility of a soil type and is calculated through extensive soil testing (Renard et al., 1991). The values between 0.10-0.45 are determined according to the contents of the soil, such as clay, silt and sand content. K factor values are also determined due to regionally specific factors such as volcanic contents and organic content (Renard et al., 1991). The original USLE uses an erodibility nomograph to determine K factor, this nomograph is modified according to such regional variables (Renard and Ferreira 1993).

Cover Management factor (C)

The cover management factor is the determination of the erosion protection provided by the above ground components of the landscape. C factors are determined in the RUSLE as a weighted average of the soil loss ratio (SLR) for a landcover and is calculated using the following formula in Renard and Ferreira (1993):

C = PLU CC SC SR SM

Where PLU represents prior land use, CC accounts for canopy cover, SC is the surface cover, SR is surface roughness and SM accounts for soil moisture (Renard and Ferreria 1993). It is considered one of the most critical factors in the RUSLE and USLE formula, as it can be directly altered and improved through management projects (Renard and Ferreria 1993). C factor classes are determined from spectral imagery using the normalised difference vegetation index (NDVI), and commonly studies will use lookup tables to assign values (Lu et al., 2003).

Support Practice Factor (P)

The P factor characterises the soil loss under specific cropping conditions. These cropping conditions include contouring and tilling, they are usually small scale and difficult to estimate (Renard et al., 1991). In recent studies the C factor has absorbed the P factor as practice factors can be described in cover management classes, and as a result the P factor is assigned the value of 1 (Benavidez 2018)

Predictive capacity: Since the USLE model is a linear model some researchers have suggested that applying it into a spatial model is inappropriate. The USLE also predicts erosion on sheet and rill erosion and neglects gully erosion which in some cases can form a large percentage of catchment soil loss. It is however able to give good estimates of overall erosion, with very little data inputs, and in some cases, performs equally or outperforms more complex models (Simms, 2007)

SOILOSS

SOILOSS is a RUSLE based computer program developed in the 1990s, it was presented as a handbook to make the process of applying the model more user-friendly manner (Rosewell 1993). The parameters used in the SOILOSS model are of interest because they have been modified from the existing RUSLE to suit the Australian landscape. Modifications included the creation of cover management (C factor) lookup tables specific to the Australian landscape and new a new classification technique for the rainfall erosivity factor (Yu and Rosewell 1996)

Predictive Capacity and Complexity: The SOILOSS model effectively exhibits the same level of predictive performance as the RUSLE model.

Study Relevance: The SOILOSS 5.1 computer program developed by Rosewell (1993) is significantly outdated. However, the modified RUSLE equations for R, LS and C factors have applications in this report.

OzMUSLE

OzMUSLE is an event based USLE model developed as a PhD at the University of Wollongong and was applied to the Cordeaux and Lake Illawarra catchments in South-eastern New South Wales (Simms 2007). Simms (2007) modified the standard formula by including an event-based rainfall intensity factor to each USLE factor, excluding the LS factor which remains universal. In this way a model such as this may account for underestimations that may occur from incorrect weighting of rainfall erosivity when only the R factor is used.

Predictive Capacity and Complexity: OzMUSLE was compared to SOILOSS and it was concluded that OzMUSLE is an improvement of 20 – 40% over SOILOSS. It is also stated that OzMUSLE performed 50% better than a ^{137}Cs based sediment loss model, however for sediment yields OzMUSLE was said to be a poor representation when compared to the values calculated from ^{210}Pb cores.

Study Relevance: The work undertaken in OzMUSLE thesis is of interest to the current report. Outside of the PhD thesis it was developed in, OzMUSLE has not received much attention in the academic space and thus the validity of its use in new studies is questionable.

SWAT

The Soil and Water Assessment Tool (SWAT) is a physics-based catchment scale water quality and erosion model developed by the USDA Agricultural Research Service (ARS), the model accounts for 44% of catchment management literature in the Scopus database (Fu et al., 2019). The SWAT model uses the MUSLE (Modified USLE) method for estimating hillslope erosion. The MUSLE model is an event based USLE model with a focus on storm events rather than long-term erosion as estimated by the RUSLE model. MUSLE modelling has also been cited as performing better than RUSLE in some Sydney basins (Erskine et al., 2002). The SWAT model is effective at estimating ecosystem health using parameters such as total suspended sediments (TSS), total nitrogen (TN), total phosphorous (TP) and overall nutrient loads over a temporal scale (Francesconi et al., 2016).

Predictive Capacity and Complexity: The model is complex and requires parameters like RUSLE, with the inclusion of streamflow values, which can be difficult to obtain in ungauged systems. Considered to be one of the most useful watershed models but does require extensive calibration to provide reliable results (Pandey et al., 2016)

Study Relevance: The SWAT model is compatible with ArcGIS and essentially becomes a toolbox called ArcSWAT, making this model easy to use when compared to other models of similar complexity. The model does require streamflow, which is limiting due to the lack of gauges in the catchment.

PERFECT

PERFECT (Productivity, Erosion, and Runoff, Functions to Evaluate Conservation Techniques) is a water balance model developed in Australia by the Queensland Department of Primary industries and the CSIRO. It is used for water management applications in agricultural areas. It requires daily rainfall inputs and soil moisture updates (Littleboy, Herron and Barnett 2003). The Office of Environmental Heritage uses the PERFECT model to create surface flow, TN, TP and TSS exports for NSW sub-basins.

Predictive Capacity and Complexity: The model's predictive capacity is said to be accurate on the annual scale but not for daily erosion (Littleboy et al., 1992). The model inputs are readily available and are crop growth, crop cover, daily rainfall, evaporation, temperature and solar radiation (Littleboy et al., 1992).

Study Relevance: Since the model was developed for use in cropped landscapes it may not be applicable for the sparsely cropped Minnamurra catchment.

AnnAGNPS

The Annualised Agricultural Non-Point Source (AnnAGNPS) model is the updated continuous model based off an earlier AGNPS event-based model. AnnAGNPS like SWAT is a daily time stepping model and is used to estimate runoff, sediment, and nutrient transport (Parajuli et al., 2008). Within the model other catchment models are combined to create the final output, these include RUSLE, CREAMS, EPIC and GLEAMS (Parajuli et al., 2008)

Predictive Capacity and Complexity: The model can account for gully erosion, giving it greater accuracy in comparison to sheet wash limited models such as RUSLE (Taguas et al., 2012). Input data and processing is comparable to SWAT making it an accessible model for most studies.

Study Relevance: The model is not extensively utilised in Australia, and thus to apply to model to the upper Minnamurra river extensive calibration would be required, which is beyond the scope of this study.

SedNet

SedNet was developed by the Australian National Land and Water Resources Audit (NLWRA) (McKergow et al., 2005). The model works by simulating river links and sub basins, creating a segmented sediment and nutrient budget (Wilkinson et al., 2009). The model has been calibrated for Australian conditions, and its success has led to an effort to develop a version of SedNet for New Zealand (Dymond et al., 2016).

Predictive Capacity and Complexity: Sednet is a good predictor of sediment and nutrient exports on the large scale, and has been applied to the 423,000km^2 Great Barrier Reef catchment in Queensland (McKergow et al., 2005).

Study Relevance: It is noted in the ewater guidelines that the model is appropriate for catchments 3 000km^2 or larger (ewater.org.au). Meaning the resolution of reporting would be inadequate for the small 115km^2 Minnamurra catchment.

CERAT

The Coastal Eutrophication Risk Assessment Tool (CERAT) is a collection of catchment and estuary models and a risk assessment framework supported by geoscience Australia (ozcoasts.gov.au). CERAT has four separate model outputs, a risk assessment, sustainable load model, catchment model and an estuary model (ozcoasts.gov.au). Of these components the catchment model provides the most useful set of outputs for this study.

Predictive Capacity and Complexity: The catchment model in CERAT is based on the 2CSalt surface flow model available on the eWater website, aided by the PERFECT water balance model (Littleboy et al., 2009). These models have been used extensively in NSW government assessments of catchment processes.

Study Relevance: The CERAT website is unmaintained and access to the models has not been possible since mid-2019 due to a database error.

WEPP

The Watershed Erosion Prediction Project (WEPP) is a versatile physics-based erosion model developed in the USA (Simms et al., 2007). The WEPP model is used around the world to simulate sediment yield and water quality in small basins (Pandy et al., 2016). It has an extensive input data requirement and requires high resolution layers (Pandy et al., 2016)

Predictive Capacity and Complexity: WEPP's consideration of a vast suit of erosion mechanisms makes it a comprehensive and effective model when time and resources permit its correct usage. Conclusions that arise from the model are often difficult to validate, interpret and many factors give very little weighting to the final outputs (Simms et al., 2007).

Study Relevance: Due to the extensive inputs required to run the model and limited time frame of this study, the WEPP model is not appropriate.

2.5 Chosen Model

Ultimately the RUSLE model was chosen to be used in this research report. The RUSLE model is a powerful empirical hillslope model which does not have intensive data and processing requirements such as physics-based models like SWAT or WEPP (Saha, Zeleke and Hafeez 2014; Pandy et al., 2016). In this way the RUSLE model suits this study as it will act to identify the main trends that are occurring in the Minnamurra catchment, which is appropriate for a pilot study of this scale.

The ability to access Australia and NSW specific methods for determining RUSLE layers also adds to the confidence in the models use. The R, LS, and C factors are created using the studies of C.J Rosewell (1993) who developed the SOILLOSS program, and the K factor layer was sourced from detailed soil studies undertaken by the NSW Department of Conservation and Land Management (Hazelton 1992). RUSLE and its factors are also well suited to the ArcGIS format, all processing can be completed using standard Arc tools. The PERFECT model is also referred to in this study in the form of a comparison to studies of catchment processes undertaken by the OEH.

2.6 Validating models

Catchment models cannot be considered as useful estimations of real-life environmental processes unless a level of validation is achieved. As such a level of uncertainty is always expected. It is however important to note that models should be taken as ‘best estimates’ unless an expansive effort has been put into providing proof of model values (Wischmeier and Smith, 1978). Generally, the more complex the model the greater amount of validation work is required (Benevidez et al., 2018). For a simple long term model such as the RUSLE it requires less, and in the case of this study we used a mixture of field sampling, visual analysis and study comparisons, which establishes a level of confidence in data trends such as erosional ‘hot spots’ rather than firm value prediction. If the analyst required certainty on the value level, then a continuous daily model such as the WEPP model is more appropriate, however this comes with a greater resource requirement (Benevidez et al., 2018). Without pre-existing long-term records of sediment movement, such as stream gauges and core records it is very difficult to provide the level of detail required by a complex model, thus an empirical approach is best suited for preliminary studies such is this report (Merrit et al., 2003).

3 Methods

To effectively model the processes that result in erosion and subsequent deposition, data of a reliable source and robustness must be attained. The approach in this study was to use the RUSLE model to identify catchment erosion trends, then validate the simulated trends using field, and lab analysis. This chapter outlines the GIS based methods that were used to create the model for hillslope erosion. This section will also explain the processes used in the field and the lab, dealing with site-based sediment analysis, as well as cross-validation with an external report.

3.1 RUSLE modelling

The Revised Universal Loss Equation (RUSLE) is an empirical model that aims to assess the amount of hillslope erosion in the form of sheet and rill erosion occurring over a given area. The RUSLE model is an extension of the original Universal Soil Loss Equation (USLE) developed in the 60s and 70s by the United States Department of Agriculture (Wischmeier and Smith 1978; Simms 2007). Updates from the original USLE include; an improved length slope equation to work with modern DEM technology, refinement in the assignment of unitless weightings to the landcover and soil erodibility factors, as well as an Australia specific rainfall determination factor from the SOILOSS model (Rosewell 1993; Renard et al., 1994; Simms 2007). The RUSLE model utilises values from the following factors; Rainfall erosivity (R) measured in MJ $mm^{-1}h^{-1}ha^{-1}yr^{-1}$, soil erodibility factor in t $h^{-1}MJ^{-1}mm^{-1}$ (K), cover management factor (C), length slope factor (L), slope gradient % (S), and erosion control practice factor (P), the sum of these factors is predicted hillslope erosion in t $ha^{-1}yr^{-1}$. The formula is as follows, and is broken down in table 2 (Renard et al., 1991):

$$A = R * K * (LS) * C * P$$

In the current state of the RUSLE the P factor has become redundant; the specific support practices of contouring, terracing and strip cropping that make up the P factor are important for plot scale applications of USLE, however on the catchment scale these are covered by agriculture/cropping in the C factor. Thus, the P factor is given a default value of 1.0 in most modern studies (Benevidez et al., 2018). In addition, these support practices do not apply to livestock pastures such as those which predominate in the Minnamurra river catchment

(Simms et al., 2003). Care was taken to ensure all layers had the same grid size as the DEM, and that all cells aligned with each other, when the final calculations were made.

Table 2 RUSLE factor summary table

Erosional Process	Determining Factor/s	RUSLE Factor	Input Data Set	Explanation	Cell labels
Rainfall		R Factor	Daily Precipitation data (BOM) (MJ.mm/(ha.h.a))	Rain splash incidence increases with intensity Higher surface flow under high intensity rainfall	
Soil erosivity	Soil Characteristics	K Factor	Digitised "Soil Landscapes of the Kiama 1:100 000 sheet" map	Hazelton (1992), assess the K factor based on particle size, organic carbon, soil structure and permeability	0 (Low) 0.035 (Mod) 0.07 (High)
Length Slope	Steepness of slopes and length of flow paths	LS Factor	5 m and 30m LiDAR based DEM	Steep slopes more likely to erode due to high effects of gravity on the landscape Longer slopes have a compounding erosion response	
Landcover	Ability of cover to mitigate rain erosion	C factor	2013 digitised landcover map, based on spectral signatures	Lack of cover increases the effects of rain splash and increases the speed of runoff	0 (Water) 0.001 (Low) 0.45 (High)
Erosion control Practice	Practices used in crop management to minimise soil loss	P Factor	N/A	In the case of cropping, erosion control measures can significantly reduce the negative erosional effects of a poorly vegetated landscape	1

3.1.1 Rainfall Erosivity Factor (R)

The rainfall erosivity factor is representative of the amount of erosive work that occurs under rainstorm conditions. The R factor is the yearly average of the energy times intensity value (EI). Rainfall intensity is the primary indicator for rainfall erosion due to kinetic forces, raindrop size and surface runoff (Simms 2007). The formula for calculating EI and R in the original USLE was formulated by Wischmeier and Smith (1978) and is represented in the formula:

$$\boldsymbol{EI = 916 + log_{10} I}$$

where E is the total storm energy in foot tons per acre inch and I is the hourly intensity. Modifications to this original formula are numerous and are undertaken to account for regional specific climate variation (Benevidez et al.,2018).

Extensive R factor testing has occurred on the Australian south-eastern coast, with a new formula coined by Yu and Rosewell (1996). The formula is written as follows:

$$\boldsymbol{E_j = \alpha[1 + \eta \cos(2\pi f j - w)] \sum_{k=1}^{N} R_k^{\beta}}, \qquad \boldsymbol{when\ R_k > R_0}$$

Where R_k represents daily rainfall and must be greater than the threshold rain event value of 12.7mm (R_o), which denotes a storm significant enough to undertake erosion work (Yu and Rosewell, 1996; Lu and Yu, 2002; Yang and Yu, 2015). **N** represents the number of rain days over 12.7mm, $\boldsymbol{f = \frac{1}{12}}$ represents seasonal variation, $\boldsymbol{w = \frac{\pi}{6}}$ is also a given co-efficient, accounting for the highest rainfall period (Yang and Yu 2015). The co-efficient **j** accounts for the month of rainfall and is not assigned a value. The final given co-efficient is $\boldsymbol{\eta}$ which is the seasonality parameter given as 0.389 for the south eastern coast of Australia (Yang and Yu 2015).

The remaining co-efficient values $\boldsymbol{\alpha, \beta}$ are calculated using the latitude of the region. The value for $\boldsymbol{\beta}$ is calculated using the following equation.

$$\boldsymbol{\beta = 1.02 - 0.0209L}$$

Where L is the latitude of the weather gauge station in decimal degrees (Yang and Yu 2015). The $\boldsymbol{\alpha}$ value is calculated using the equation.

$$\boldsymbol{\alpha = 1.05 \times 10^{(2.08 - 1.58\beta)}}$$

The R factor is the sum of monthly rainfall erosivity given (MJ mm ha-1 hour-1 year-1).

Precipitation data was sourced from the Bureau of Meteorology (BoM) SILO program, hosted by the Queensland Department of Environment and Science. SILO point data provided precipitation values for three locations in the catchment, from as early as 1890, values were averaged from 1960 onwards.

3.1.2 Length Slope Factor (LS)

The length slope factor is the sum of the slope length (L) and the slope gradient (S) for a given topographical profile. The slope length was determined using the 5 m DEM from aerial derived LiDAR points and filled using the fill tool to eliminate imperfections in the DEM that would affect drainage patterns. The final outputs were 30m and 5m resolutions, as the STRM derived 30m resolution covered the entire catchment, where the higher resolution LiDAR had missing sections in the upper catchment. From the DEM, flow direction was determined for each cell using the flow direction tool in ArcMap; this determined the general path of flow from an upslope to downslope direction. Using the flow direction layer as an input, the flow accumulation tool was used to generate a slope length layer, which was a representation of the water paths across the landscape, as indicated by the DEM. The slope gradient layer was created using the slope spatial analyst tool and represented in percent rise. An empirical formula that incorporates flow accumulation, slope and elevation, was used to create the LS factor, which accounted for the erosional effects of increasing slope angle and length (Mitasova et al., 1996; Simms 2007).

LS = Power(Flow accumulation * DEM resolution / 22.1, 0.4) * Power(Sin(Slope percent rise * 0.01745 / 0.09), 1.3)

The LS factor can be calculated using standard spatial analyst tools in ArcGIS; however, calculation errors occur resulting in the Sine function in the above equation leading to NoData scores, and thus significant data gaps. To mitigate this issue the TauDEM plug in was used, as it has output values for slope in radians which negates the need to include a Sine function to convert slope percent to radians (Tarboton 2003). The LS factor calculation from initial DEM input to RUSLE compatible layer is represented by the model in figure 2.

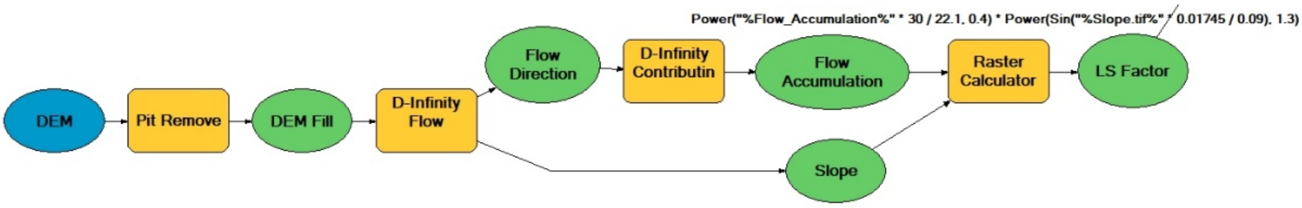

Figure 2 ArcMap model showing the steps used to process the LS factor. 1. Fill pits/sinks in the source DEM, preventing flow interruptions for the next steps 2. Calculate the flow direction using D-infinity flow, this tool also calculates a second parameter, which is slope in radians 3. Calculate the flow accumulation with D-infinity Contribution using the Flow direction layer as the input 4. Use the LS formula in raster calculator to create the final output, using slope and flow accumulation.

The LS factor is the most complex factor in the RUSLE equation, it is also a variable factor depending on the resolution of the DEM used (Shan, Yang, and Zhu 2019). Advances in technology in recent years has given way to high resolution elevation data of 10m-1m variation. It may be expected that in all cases the higher the resolution the better, however (Shan, Yang, and Zhu 2019) suggest that in areas of extended spatial homogeneity i.e. flat low elevation areas, a 1m DEM may result in excess noise that could result in errors in the LS factor. Therefore, a lower resolution 5m DEM was applied to this study, to mitigate these errors.

3.1.3 Soil Erodibility Factor (K)

The K soil erodibility factor is an empirically derived value which is used to determine the erodibility of a soil from the characteristics of soil texture, organic matter, structure and permeability (Simms 2007). Soil samples from the Kiama region were studied and classified in the Soil Landscapes of the Kiama 1:100 000 sheet, with K values included for each soil classification (Hazelton 1992). The classifications follow the SOILOSS guidelines for Australian erosion predictions (Rosewell and Edwards 1988). Hazelton (1992) clarifies the levels of erodibility using the following classes (Table 3). Soil profiles in digitised vector form was adjusted to include K values in the associated shapefile attribute table. As all layers needed to be in raster format for final RUSLE calculation, the ArcMap conversion tool polygon to raster was used to create the K factor layer for use in the RUSLE calculation.

Table 3 Soil erodibility lookup table (Hazelton 1992)

Erodibility potential	K Value
Very low	0.00-0.001
Low	0.01-0.02
Moderate	0.02
High	0.04
Very High	>0.06

3.1.4 Cover Management Factor (C)

The cover management factor indicates a unitless erosion value on landcover classes according to spectral based measurements of landscape cover using NDVI. NDVI techniques categorise land use based on their spectral signatures, allowing a landscape to the subdivided in broad categories such as forest, pasture and urban land, and further into specific classes within this range, such as native rainforest, livestock grazing, and transport services. Land which is highly vegetated is well protected from the erosional forces of rainfall due to increased canopy cover, root mass, and surface roughness, which interrupts the incoming rainfall reducing its erosive effect. Vegetation also improves the soil matrix providing improved soil cohesion and decreases the erosive effects of surface runoff. Poorly vegetated however suffers from poor soil cohesion, increased runoff and lack of rain splash protection. To represent this C factors, range from 1 – 0 where a value of one represents a barren landscape and close to 0 represents a dense forest system. In the study the values used are derived from Australian studies of C values by Rosewell (1993). Using a categorised landcover layer for the year 2013, clipped to the Minnamurra catchment, C values were added to the attribute table 3X using the following values:

Table 4 Landcover classes and corresponding values

Land cover type	C Value
Pasture/Grassland	0.3
Intensive Agriculture and cropping	0.45
Native Forest, Wetlands and Saltmarsh	0.001
Softwood plantation and Grazing vegetation	0.009
Urban, Residential, Services (there is some evidence to say that these areas may have lower erosion than I have used)	0.45

The conversion tool ‘polygon to raster’ ArcMap tool was used to create the C factor layer for use in the RUSLE calculation.

3.1.5 Predicted hillslope erosion

Predicted hillslope erosion is the product of all the factors described in chapter 3.1, R, K, LS, and C, created with the raster calculator. To maintain the appropriate resolution, care was taken to keep the cell size in each layer consistent and aligned using the Snap Raster environmental setting in ArcGIS.

A sub-basin scale analysis was also undertaken to provide a clearer picture of the trends in the RUSLE output. To analyse sub-basin scale erosion, the zonal statistics spatial analyst tool was used in conjunction with the predefined sub-basin map provided by the OEH (Figure 3). The tool allowed the average erosion (tons/ha/yr) per cell in each sub-basin to be calculated. The intention was to create a map that was easier to decipher than the basic RUSLE output to help with management recommendations, and to provide a map that was simple to compare with the maps created in the OEH's studies.

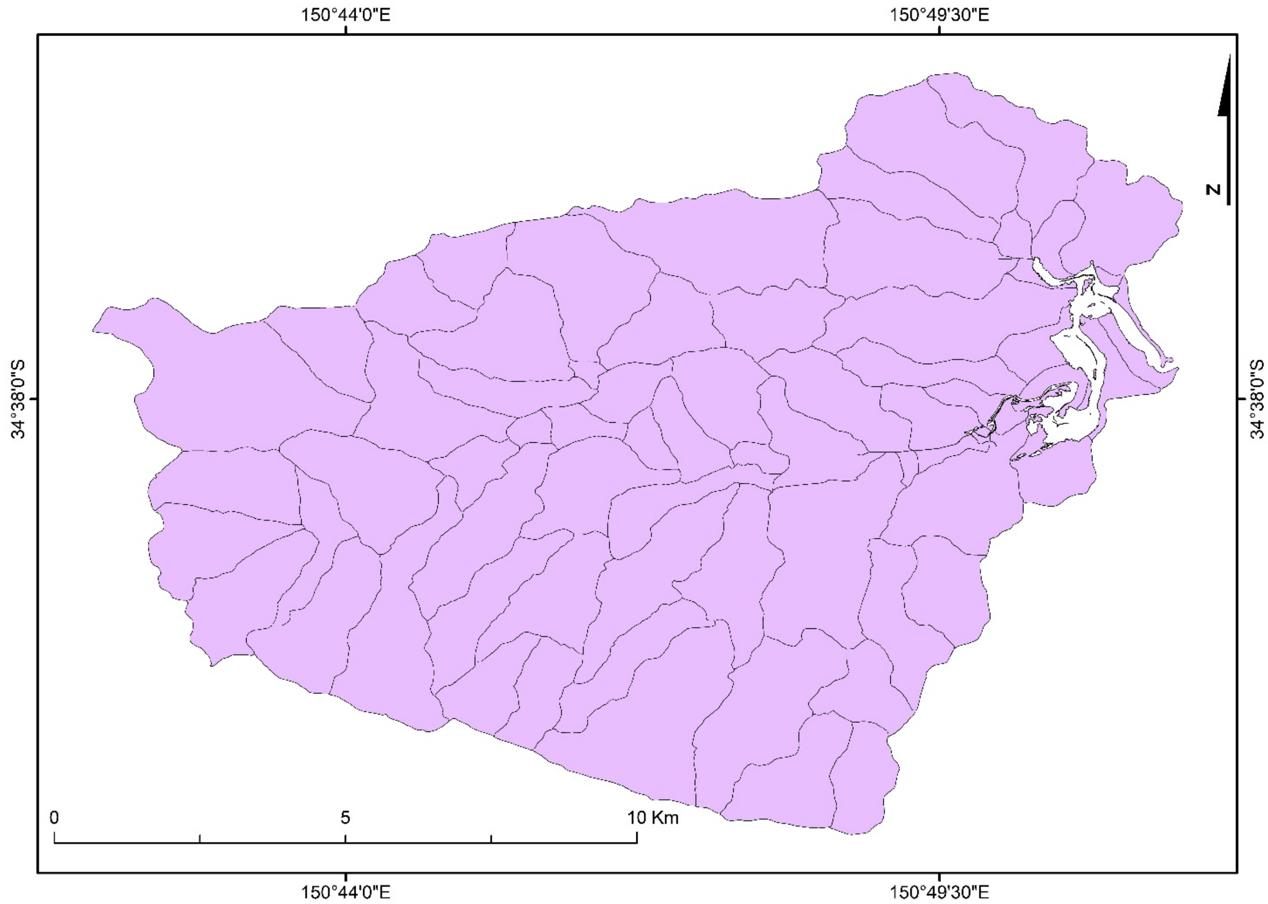

Figure 3 OEH defined sub-basins for the Minnamurra river catchment

3.2 RUSLE Sensitivity Analysis

In a review of the RUSLE model Benavidez et al, (2018) suggest that undertaking a sensitivity analysis on each sub-factor used in the model is important before the final solution is reached, to asses which factor contributes the most to the RUSLE output.

LS and R Factor

The LS and R factors are both determined using complex equations, thus the final product is significantly altered from the input data used. The input data in these cases are the DEM and daily precipitation for LS and R respectively. These inputs were altered by ±10%, and then used in the RUSLE equation from chapter 3.1. The changes in the RUSLE mean (ton/ha/yr) were assessed as well as the changes in class distribution. To assess changes in class distribution the RUSLE output was reclassified to create a viewable attributes table, which could then denote the changes in each class when the input data was changed by ±10%.

C and K factor

The C and K factor are both weighted factors that are directly inserted into pre-existing attribute tables. The C factor is assigned according to land use class as categorised in the lookup tables in the previous sub chapter. Two land use layers were provided for use in this report. The 2013 NSW land use layer categorised using a combination of aerial photography and SPOT5 imagery at a map resolution of 1:10,000. The second layer provided was the NSW land use for 2002 categorised using aerial photography with a map resolution of 1:25,000. The same reclassification method used to compare the R and LS factors was used to compare the percentage difference between the 2002 and 2013 C factor RUSLE outputs. The K factor was valued according to soil classes determined by Hazelton (1992) at a 1:100,000 scale without an alternative higher resolution method, so its sensitivity could not be assessed.

3.3 RUSLE Validation

Models are not considered valid unless the trends observed can be backed up significantly with sample-based results or through the comparison of similar studies. Simms (2007) outlines that validation is the act of providing legitimacy, and is distinct from verification, which is providing truth, which cannot be determined in open systems such as a catchment. Therefore, the aim of validation in the case of this study, is to attempt to identify the trends observed in the RUSLE output through field sampling and comparisons with other models. To appropriately account for exact erosion values, temporal environmental markers such as radioactive elements such as Carbon-14, and Caesium- 137 should be used, however these methods lay outside the scope of this report (Simms 2007). Instead this study uses common sample techniques such as water sediment sampling, river cross section streamflow analysis and model comparisons, to establish valid *data trends* as opposed to values.

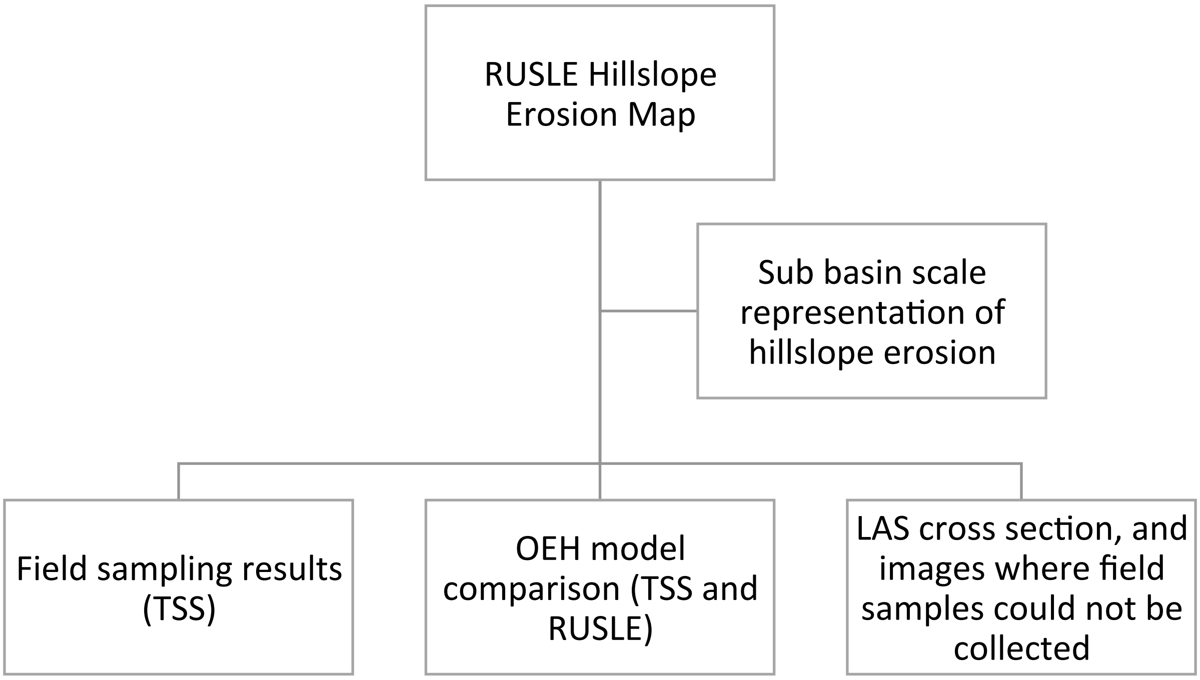

Figure 4 RUSLE validation flow chart

3.3.1 Field Water Sampling

The study consists of two fieldwork components. The first component is water sampling on two days, one dry sample day and one sample day following a rainfall event. These samples were stored below 4^{o}C until they could be analysed in the lab. Rainfall event sampling was limited by low rainfall during the February- September period, with only three events surpassing 12.7mm of 24hr rainfall.

The core focus of field sampling was to identify patterns of sediment transport in the catchment so that they can be compared to trends observed in the RUSLE model. In this way total suspended solid contents (TSS) was measured at 9 locations in the catchment, that give a representative sample of sub basins (Figure 5). TSS to correlated to the transport of eroded material and indicates where erosion was occurring. One complete run of dry condition samples was collected on the 15/08/19 and two rainfall events were sampled on the 30/08/19 after ~40mm of rain and the 19/09/19 after ~60mm of rain. The dry and wet sample days were carried out to observe if there is a significant input of sediment as a result of rain and if there are any significant ongoing sources of sediment delivery into the river and tributaries during dry periods. It must be noted that the tenth sample location of Turpentine Creek did not reach a flow state following either sampled rain event but was flowing after rain of 45mm on the 4th of April 2019.

In order to provide an extra degree of confidence to TSS results, a field meter was used. Using the conductivity probe calibrated to a 1413μs/cm standard, samples were analysed in the field, following collection. The primary variable measured here was total dissolved solids (TDS), which provides some validation to the TSS values measured.

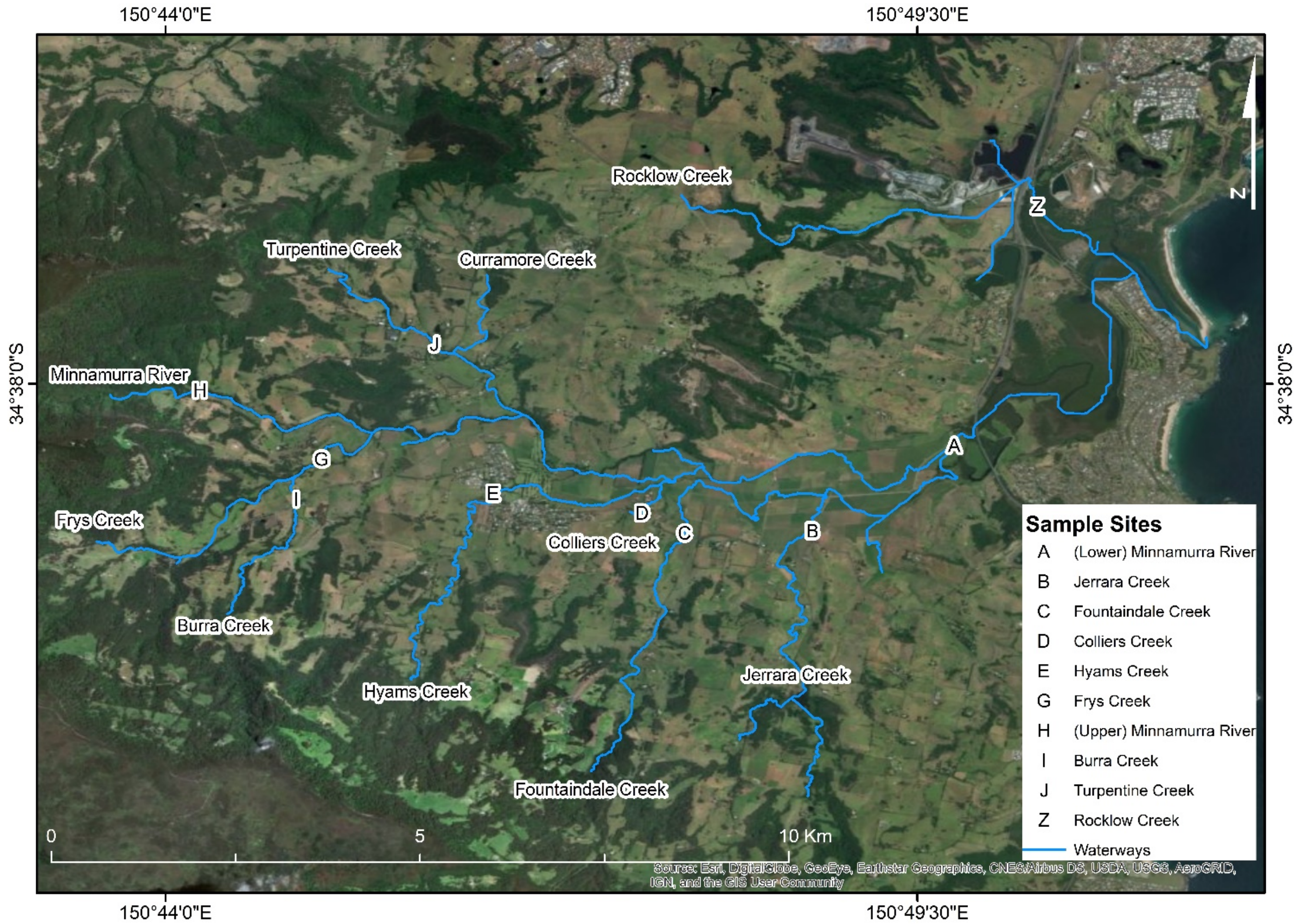

Figure 5 Water sample locations

3.3.2 Lab Water analyses

Lab analysis was comprised of 2 measurements; particle size analysis and measurement of Total suspended solids (TSS). Two runs of TSS were completed using university laboratories and one run was completed at ALS environmental professional labs.

Particle Size analysis

The Mastersizer 2000 was used to identify particle sizes in water samples following a rain event of 45 mm/day and after a period of <1mm/day rainfall. The Mastersizer 2000 uses laser diffraction, to measure the composition of sediments in a water sample. The Mastersizer provides an analysis of sand, silt and clay contents, which can be used to determine the sedimentation characteristics of an area. It also calculates the average size of sediment grains, which is used in conjunction with sediment characteristics to see how much sediment transport 'work' is occurring in the creek or river.

Total Suspended Solids

The procedure used to determine TSS in tributary water samples follows the EPA method 160.2 (1983). This sample method is appropriate for TSS contents of up to 20,000mg/L, and has a detection limit of 0.5mg/L.

500ml samples (500ml x 2 for each site) of river and creek water were collected on the 15 August 2019 dry period samples were collected. Waterways within the study that were collected on this date were; Rocklow Creek, Minnamurra River, Jerrara Creek, Fountaindale Creek, Hyams Creek, Frys Creek. Burra Creek, Turpentine Creek, and Colliers Creek were too dry for the collection. On the 19 September 2019 rainfall event samples were taken from all creeks except Turpentine Creek which remained dry.

The samples were kept in an esky with ice bricks for one day and then taken to the university lab, where they were transferred to a fridge where they were stored at 4^{o}C for less than 7 days to avoid decomposition of organic solids. Glass filters were pre-dried for 1 hour at 104°C then weighed; this followed a filter rinse of 2 lots of 200ml distilled water, to remove any potential contaminants. Samples of 500 ml were filtered through the vacuum pump apparatus and then rinsed with 600 ml deionized water. A deionized water blank was used, so that losses due to filter damage could be estimated in order to adjust the final sample weights and to provide a baseline reading.

The filtered samples were transferred to aluminium trays and dried in an oven at 104°C for 1 hour again. The dried filter samples were then weighed on an analytical balance and recorded to 0.1mg after they were left to cool in a desiccator for 10minutes. The formula below was then applied to determine TSS.

$$\text{TSS} = \frac{\text{Dry mass mg} - \text{Filter weight mg}}{\text{sample volume ml}} * 1000$$

ALS laboratory's

ALS laboratories use the sample technique that was undertaken during university testing; however, their reporting comes with enhanced rigour as more experienced technicians carried out the analysis. They registered a limit of recording of TSS at 5mg/L. This TSS analysis was used to provide a factor of validation to the TSS analysis conducted in this study. The lab also conducted a nutrient analysis, that can be considered representative of organic load into the water courses sampled. The nutrients sampled were total nitrogen (TN) and Total Phosphorus (TP). Both analytes were measured to a reporting limit of 0.1mg/L.

3.3.3 Stream cross-sections

Cross sections of nine river and tributary locations were created using a level and surveying pole, at the water sample locations in figure 5. This is undertaken to calculate stream parameters allowing the estimation of approximate streamflow at different sections of the catchment. Flow velocity was calculated using a float and a timer, as well as a field tape to measure flow distance from point a to point b. Once river cross sections were completed, the bank full height was estimated in the field. This was then used to calculate the bank full cross section of the segment in m^3. By taking the product of flow velocity (average float time [s]/segment length [m]) and the bank full cross section (m^3), an estimate of the bank full Discharge (m^3/s) was achieved. The stream cross sections were used to assess which waterways in the catchment would distribute the most sediment throughout the catchment. To do this, the TSS measurements were converted to kg/L and multiplied with the bank full discharge in L/day to estimate sediment yield in kg/day.

3.4 Model comparison

The catchment analysis undertaken in this study was compared to state-wide studies of catchment processes carried out by the Office of Environment and Heritage (OEH). The OEH has run models such as PERFECT, and RUSLE to simulate the effects of erosion, sediment and nutrient transport rates.

Validation of result comparison was carried out in two ways. The first was a visual analysis that involved an initial comparison of the unedited RUSLE output with the OEH RUSLE and TSS maps to identify trends and noting similarities and differences. Following this, predefined OEH sub-catchments were used to create a zonal statistics map of the OEH RUSLE and the RUSLE of this study to compare the zonal means of each model. It should be noted that the OEH RUSLE formulation is produced at a 30m resolution (Yang 2015). Trends were also compared between TSS formulations and the RUSLE hillslope erosion zonal means, to provide a link between these two measurements.

In addition to erosional trends, nutrients were also considered in this study. Using OEH model maps of total nitrogen (TN), total phosphorus (TP) and the nutrient results from ALS laboratories, correlations could be deduced. The results from ALS laboratories gave an indication of nutrient loads in each tributary basin. These were compared with the predictions in the OEH nutrients models and used to identify trends. This method would require further validation through replication and high-resolution model formulation, as the OEH study covered a broader area than the Minnamurra catchment.

4 Results

4.1 RUSLE modelling

The RUSLE model provides an estimate of the hillslope erosion that occurs on a catchment scale. The four factors, R, LS, K, and C are also smaller scale models themselves, and thus need to be investigated to understand their individual trends.

4.1.1 Rainfall Erosion Factor (R)

The rainfall factor represents the intensity of rainfall and its ability to carry out erosion work in the form of sediment mobilisation and transport. In figure 6 the map shows that rainfall intensity increases in a westerly direction. When considering the topography of the Minnamurra catchment the greater rainfall occurs moving up the western ranges, in this case Jamberoo Mountain towards Robertson. In this way the upper catchment areas which include the tributaries of Fry’s Creek, Turpentine Creek and the main river section experience heavier orographic rainfall at their elevated headwaters. The values in the R factor are interpolated (kriging) from three stations in the catchment. These stations had the following values once precipitation data was converted 5366.1MJ.mm/(ha.h.a) (Kiama Township), 8371.6 MJ.mm/(ha.h.a) (Jamberoo Township), and 8866.0 MJ.mm/(ha.h.a) (Upper Catchment)

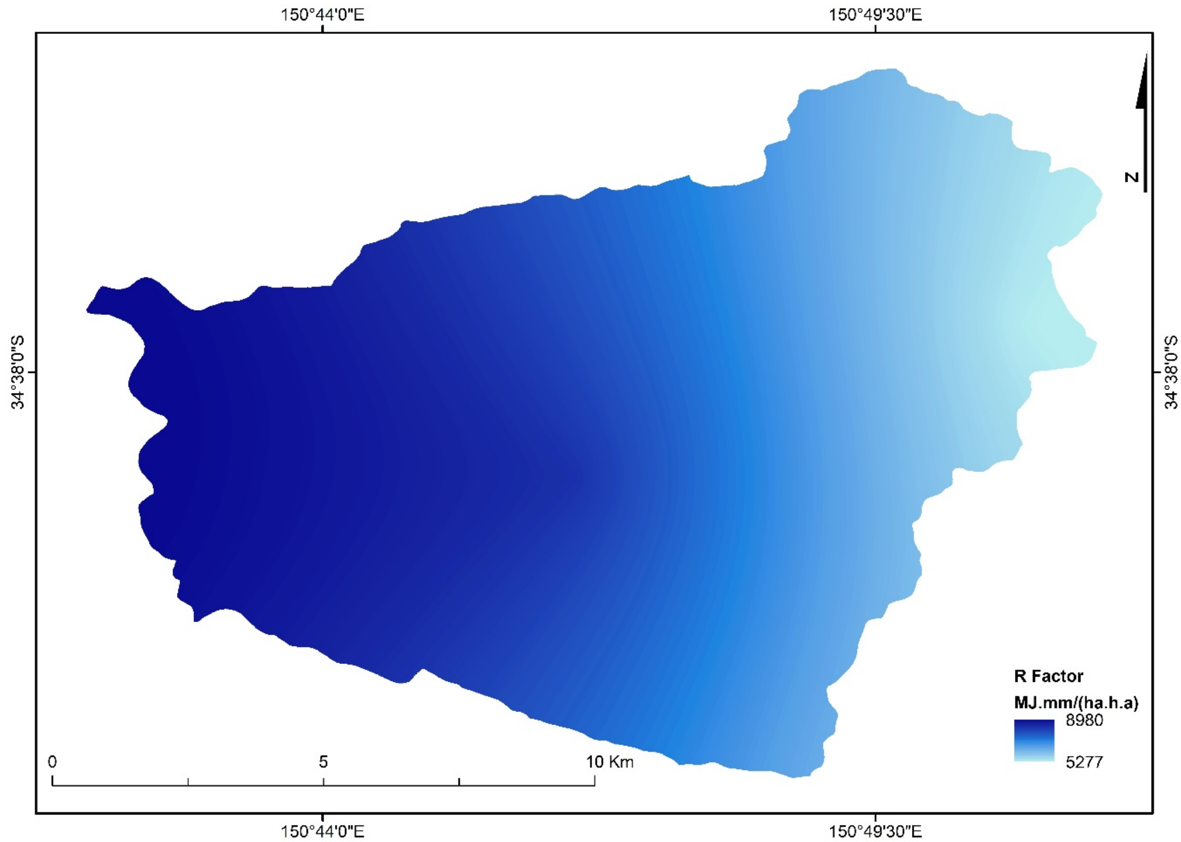

Figure 6 RUSLE R factor map, derived from precipitation station data

4.1.2 Length Slope Factor (LS)

Length slope analysis on the DEM revealed the trends in figure 7 and 8. The highest values occur at the peak of hills in the catchment. This correlates to the steepest slopes in the catchment, which have the greatest erosion potential. The lowest values for LS occurred in the floodplain area where the topography is flatter. The 5m DEM provided higher resolution representations of the topography and shows the variation in high medium and low values. The 30m DEM shows less of the intricacy of the landscape, however it does not suffer from edge contamination in the western section of the map, where incomplete DEM tiles are included. The values of the LS factor are unitless.

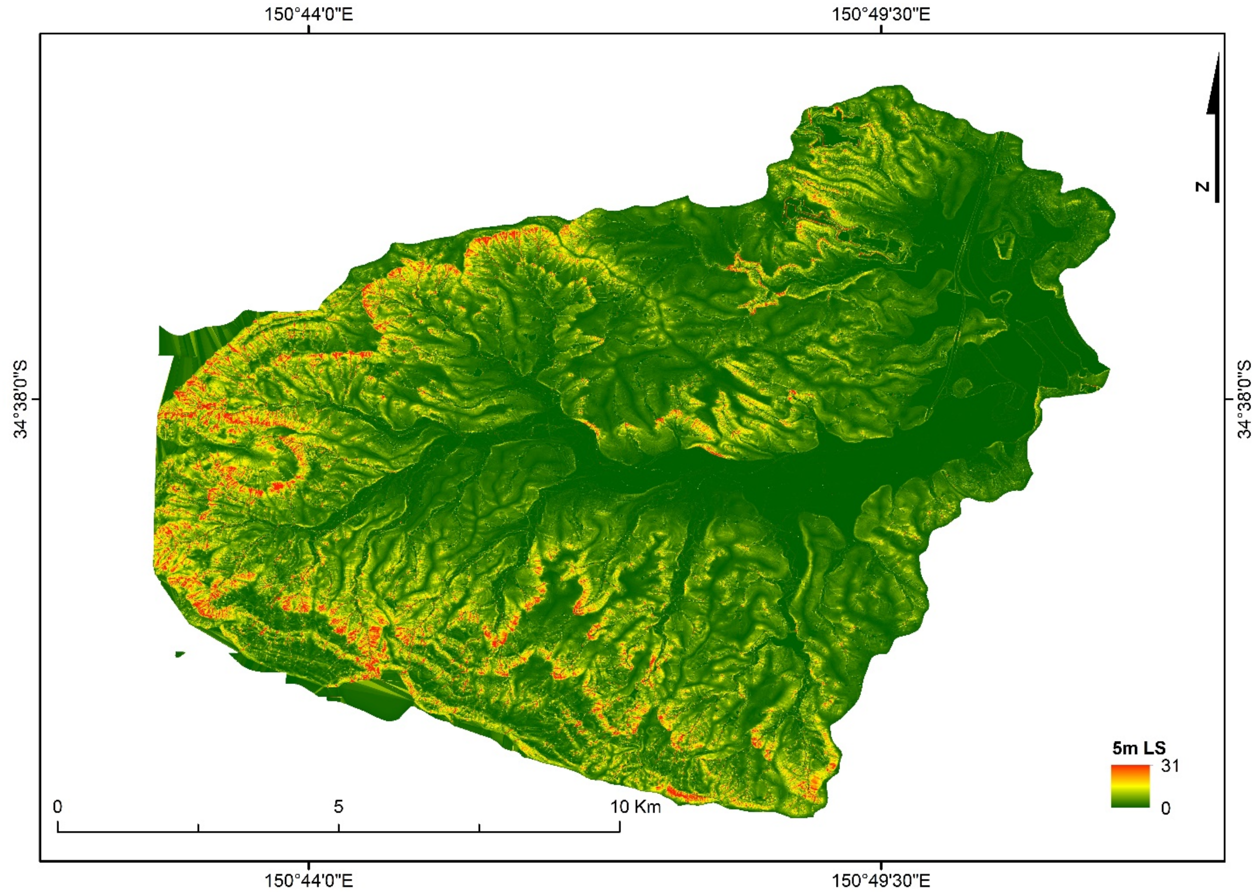

Figure 7 5m RUSLE LS factor map

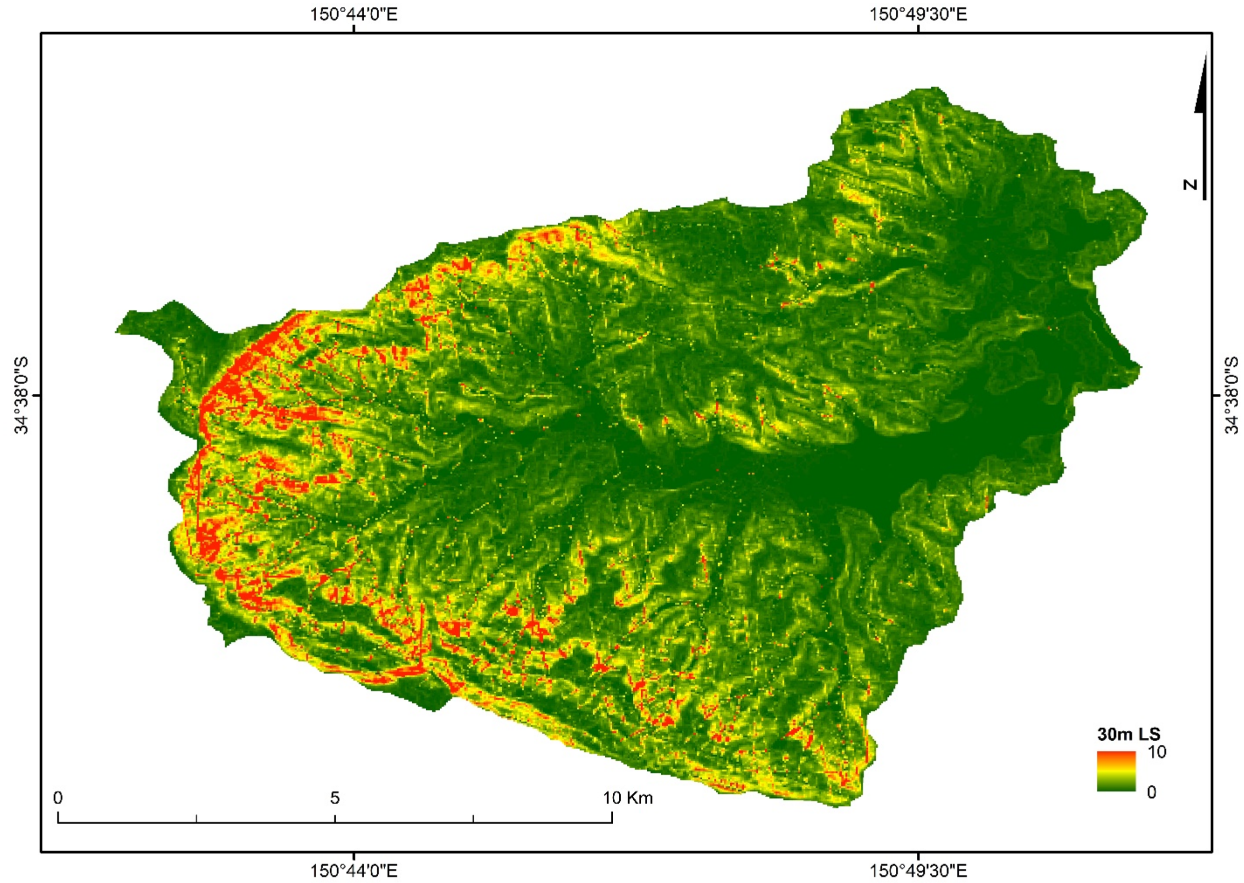

Figure 8 30m STRM DEM LS factor, whole catchment is covered, which is not achieved using LiDAR derived data

4.1.3 Soil Erodibility Factor (K)

The K factor map created from the Hazelton 1:100,000 sheet is represented in figure 9. Soils were given a ranking according the measured characteristics in bulk soil groups by Hazelton (1994). The alluvial landscape surrounding the floodplain has a low value of 0.02 and water is given a value of 0. Values of 0.07 are given to areas considered ‘disturbed’, within the catchment, quarries and special works such as landfill exhibit this value. The highest K value for regular soils is 0.061, this is given to the Shellharbour soil group. Most of the catchment is composed of the Bombo soil group, which is sourced from the Bumbo latite geology layer, and exhibits a K value of 0.035. The Fountaindale and Wattamolla road soils are given values of 0.04. Above the catchment and on higher elevations, the soil groups of Jamberoo, Cambewarra and Barren grounds have low K factor values of 0.03 (Jamberoo and Cambewarra) and 0.01 (Barren grounds), indicating the apparent stability of these hillslope soils.

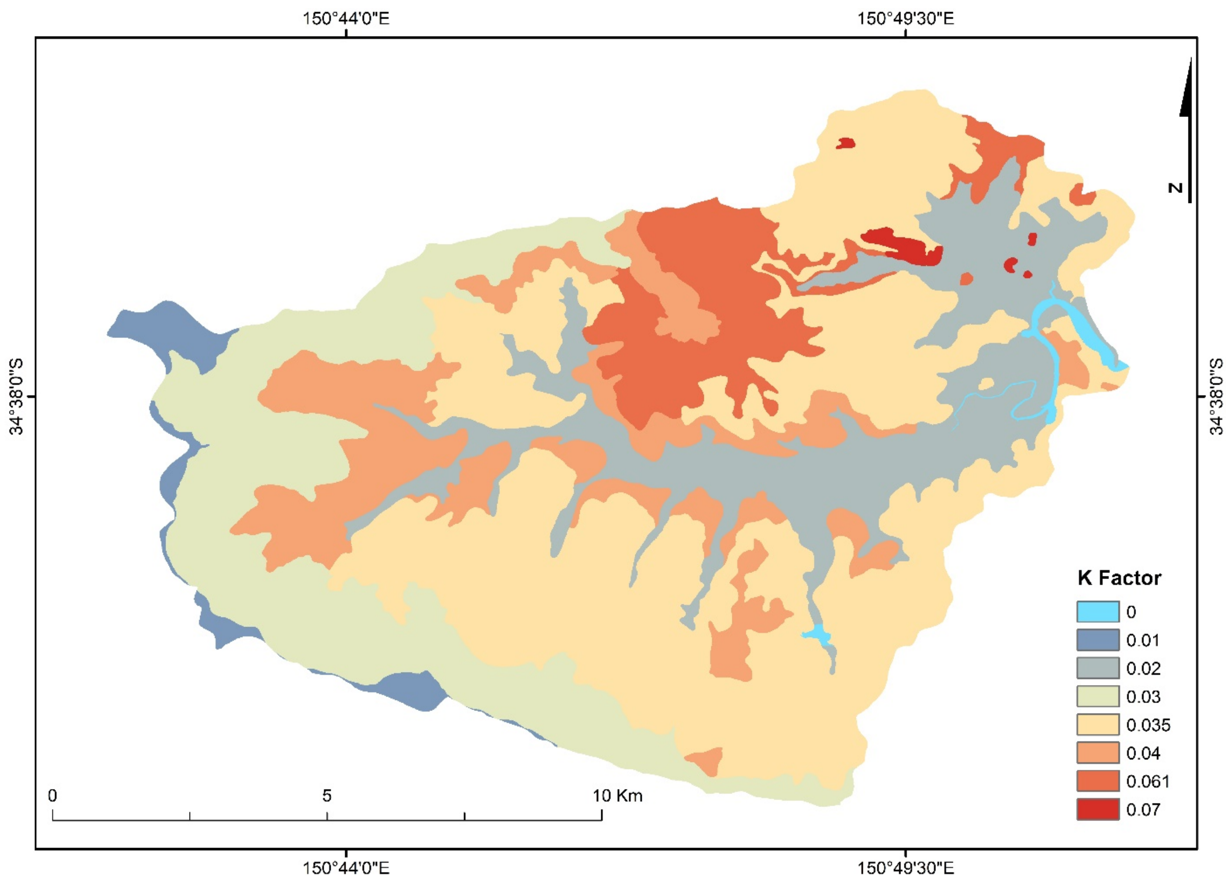

Figure 9 RUSLE K factor map

4.1.4 Cover Management Factor (C)

The cover management component of the RUSLE model is represented in figure 10. Most of the catchments highest C factor values occur around lower slopes where farming activities have been established. Generally, a value of 0.3 has been applied to the grazing pasture sections of the catchment. More intensive agriculture such as piggery's, Quarry's, urban areas such as Jamberoo and Kiama Downs townships are given the highest C value of 0.45. Areas with semi cleared native vegetation have the value of 0.3. Areas with minimal use and some remnant native vegetation have a C factor of 0.009. Residual native cover is given 0.003 and usually occurs on hillslopes that were not suitable for pastureland. The lowest C factor of 0.001 occur in the upper catchment Minnamurra rainforest national park and Barren grounds reserve where vegetation is the most established, as well as along the mangroves and saltmarsh areas of the River estuary.

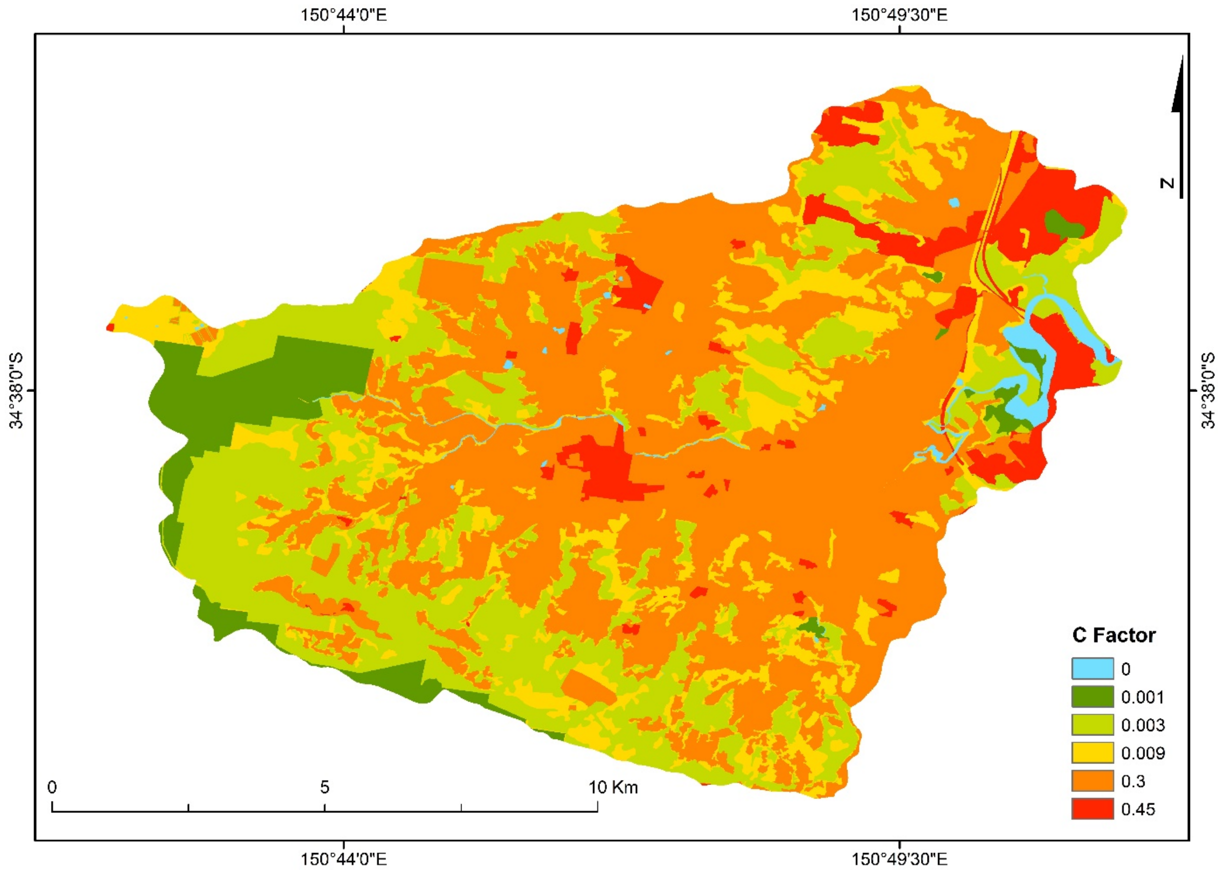

Figure 10 RUSLE C factor map

4.1.5 Predicted Hillslope Erosion

The RUSLE hill slope erosion output measures erosion in tons per hectare per year. The RUSLE model shows that the areas of consistent >12ton/ha/yr hillslope erosion occur where there is significant slope steepness (figure 11 and 12). On the alluvial plain where slopes are low, very little erosion occurs. The most erosive regions appear when high slopes and poor landcover is present (see Figure 10). Examples of this include pastures on slopes such as those found in Curramore and the headwater reaches of Fountaindale, Hyams and Jerrara creeks. Quarry landcover is also particularly erosive, as it is bare land on a hillslope. Steep slopes that are well forested do however exhibit much lower erosion; this is especially clear for the Minnamurra rainforest. It is not clear whether the soil erodibility K factor is having a significant impact in any part of the catchment. There is also no clear increase in erosion moving up in the catchment as a result of rainfall erosivity, as the topography generally is the main increasing factor moving up (west) the catchment.

The comparison between the 5m RUSLE in figure 11 and the 30m RUSLE in figure 12 indicates how much overestimation occurs as a result of lowered resolution. Features such as the Quarries in the north east of the catchment are more defined in the higher resolution image, and the gradation of erosion is easier to observe.

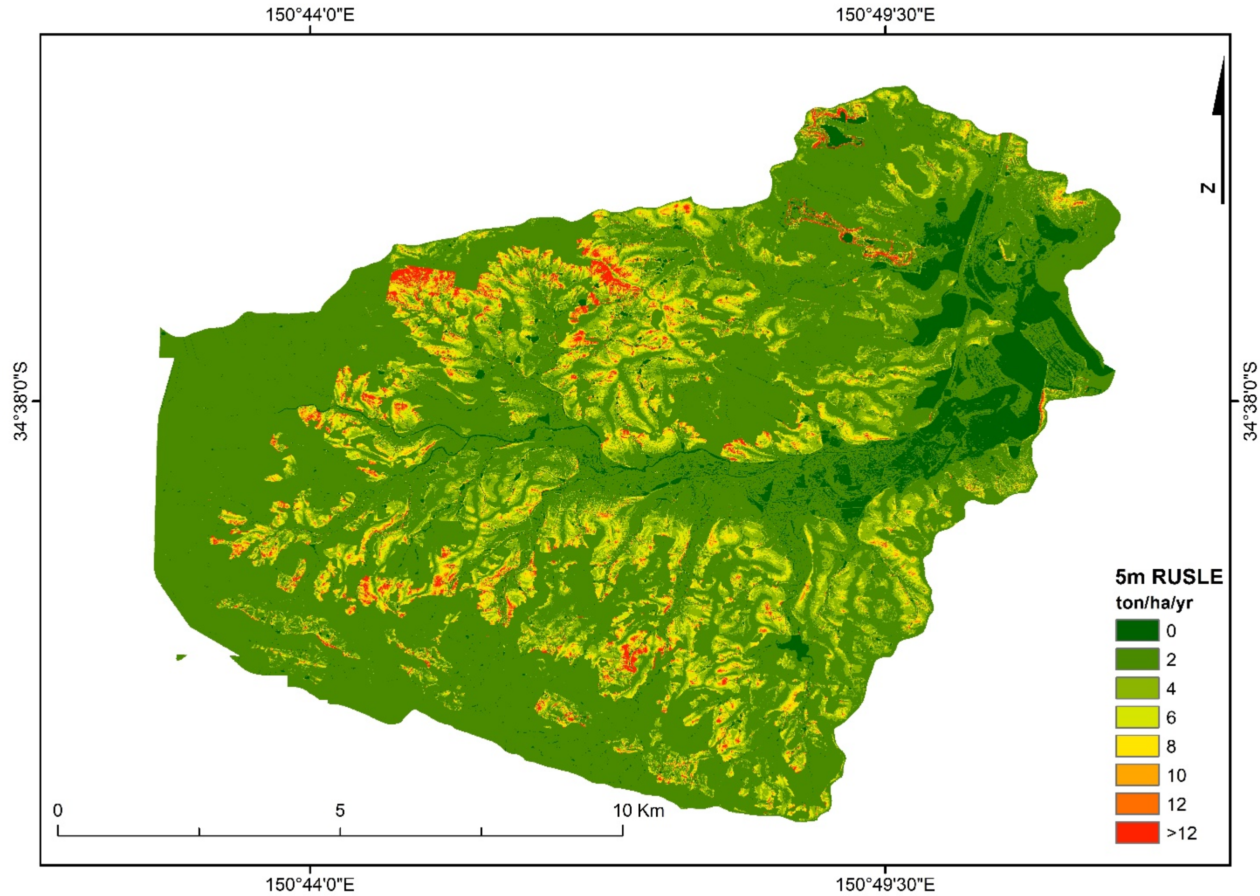

Figure 11 RUSLE derived hillslope erosion, from 5m DEM data

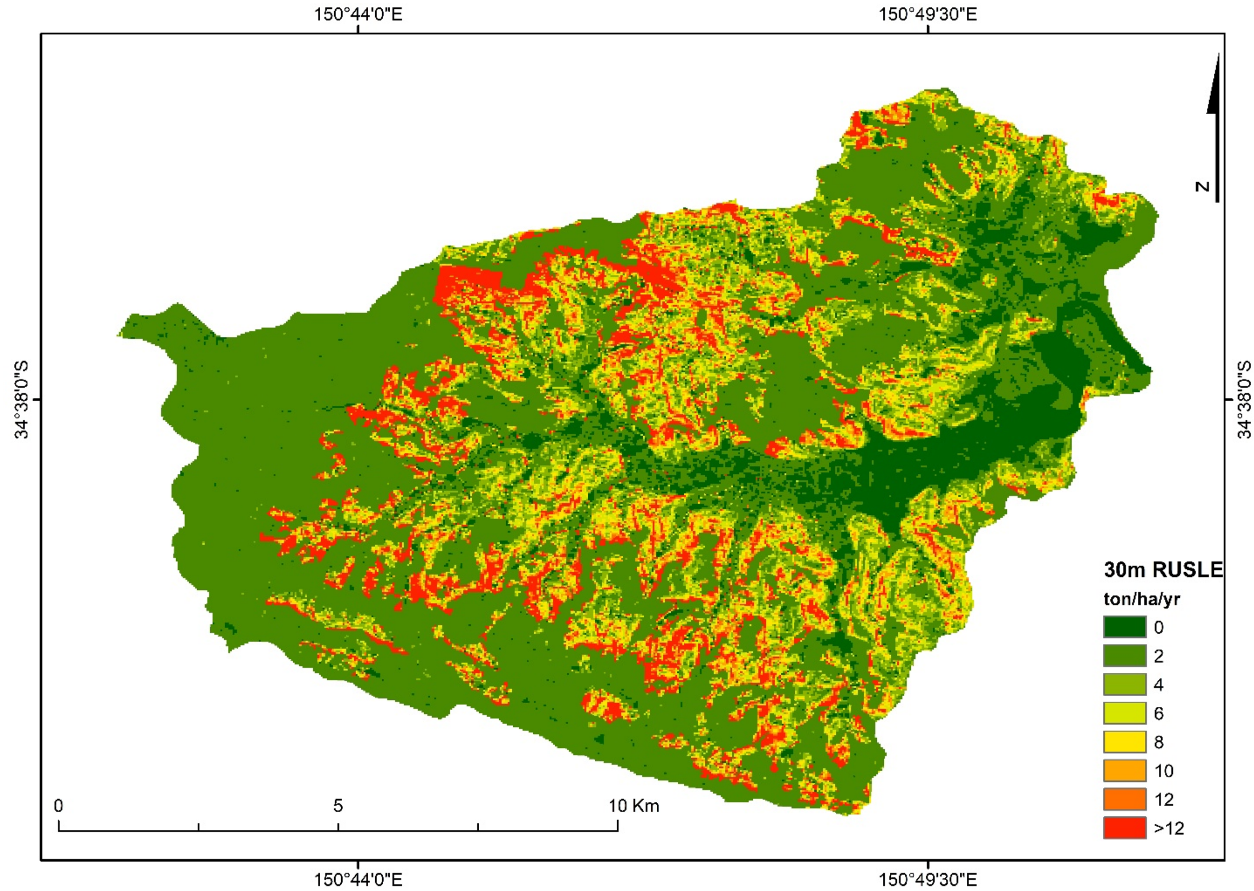

Figure 12 RUSLE hillslope erosion, derived from a 30m DEM

Figure 13 shows how the erosion seen in figure 11 and 12 is represented in a sub basin form. The values characterise the average amount of erosion occurring per cell in each of the Minnamurra catchment sub basins. The map provides a simplified representation of catchment erosion, allowing trends to be easily pinpointed. It can be observed that there are two areas of higher erosion in the map. The first noticeable area of significant erosion is in the north of the catchment, this area covers the headwaters of Turpentine and Curramore Creek to the east and Rocklow Creek to the West. The headwaters Rocklow Creek is significantly located close to the Dunmore Quarry which may explain the trends here, where topography is less significant. The Curramore region which includes Turpentine Creek is an example of an area with agricultural practices occurring on significant slopes. The second noticeable area of high erosion is the South Eastern section of the catchment, which covers Jerrara, Fountaindale and Hyams creeks.

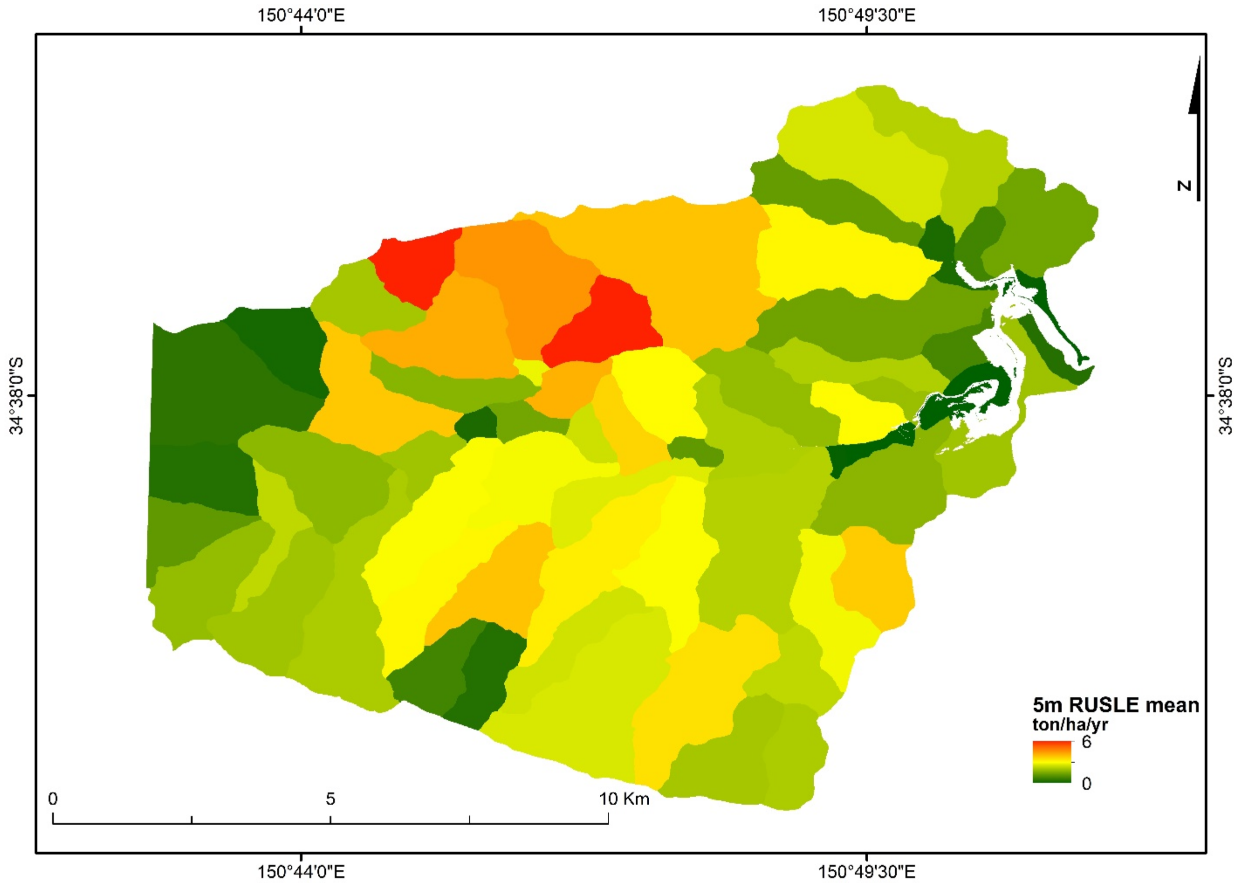

Figure 13 RUSLE derived hillslope erosion, from 5m DEM data. Converted using Zonal statistics to display the mean erosion in tons per 60x60 raster pixel.

Figure 14 shows the spread of data in the 5m RUSLE output. The RUSLE calculation tends to produce maximum values that are very far from the bulk scores. The histogram shows that most hillslope erosion values for the maps 5mx5m cells, fall in the 0-25 ton/ha/yr range. Within the range of 0-25ton/ha/yr 11531.1ha of the 11537.7ha catchment is covered, the 25-50ton/ha/yr class covers 5.4ha. The remainder of the classes 50-1000ton/ha/yr cover only 1.3ha of the catchment and thus these higher values can be discounted as insignificant. It should be noted that m^2 is used rather than hectares for the vertical axis in figure 14 as the decimal places in the lower scores produced errors when converting to $\log_{10}$ scale.

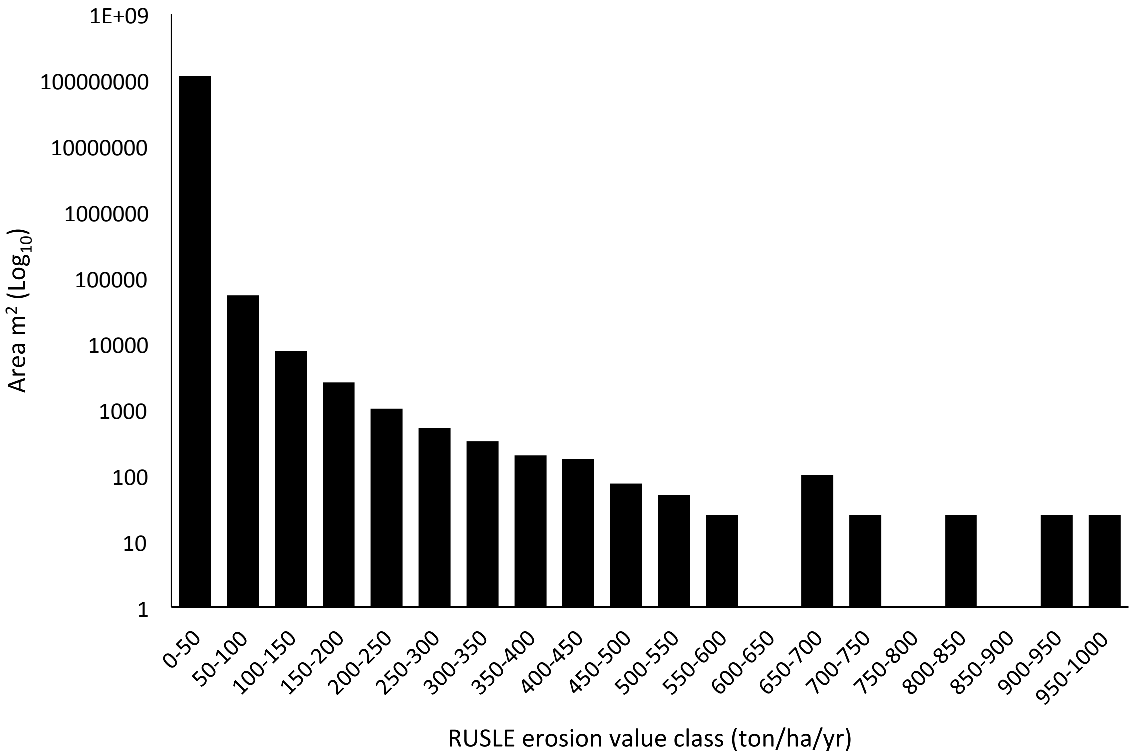

Figure 14 Base 10 log scale histogram showing the spread of erosion values in the 5m RUSLE

4.2 Sensitivity analysis

R and LS Factors

Tables 5 and 6 shows the difference in sensitivity between the R and LS factors. Using a 5m DEM and the standard unchanged input factors the mean soil erosion throughout the entire catchment is 0.82ton/ha/yr. When precipitation values going into the R factor equation are decreased by 10% this mean becomes 0.68ton/ha/yr and when they are increased by 10% the mean is 0.98ton/ha/yr. This represents a total change of 17.1% (-10%) and 19.5% (+10%). When the DEM is used to calculate the LS factor is decreased by 10% the mean is 0.71ton/ha/yr and when it is increased by 10% the catchment mean is 0.94ton/ha/yr, representing a 13.4% and 14.6% change respectively. Therefore, using the current inputs of this study, the RUSLE model is more sensitive to changes in the R factor than the LS factor.

C Factor

The difference in the RUSLE output using the 2002 and 2013 C factors is displayed in table 5 and 6. The catchment erosion mean for 2002 is 0.62ton/ha/yr compared to the mean of 0.82ton/ha/yr observed in the 2013 C factor, this represents a 24.4% difference. Notably, even though overall the 2013 C factor estimates higher total erosion, the 2002 C factor resulted in an 81% increase the maximum erosion value and a 43% increase in pixel values located in the highest class.

Table 5 Sensitivity values after 10% change in R and LS, and difference between the 2002 C factor

Class (ton/ha/yr)	5m RUSLE (ha)	10% * R (ha)	10% * LS	2002 C
0	813.75	813.75	813.75	809.78
0-2	7692.60	7368.58	7459.84	7034.69
2-4	1499.25	1438.26	1460.96	1739.77
4-6	753.35	846.79	823.90	912.90
6-8	352.22	448.22	419.70	449.11
8-10	171.30	240.47	219.87	229.35
10-12	89.60	131.27	117.19	124.98
>12	165.64	250.36	222.49	236.31
max	1048.34	1250.00	1168.04	1903.23
mean	0.82	0.98	0.94	0.62

Table 6 Score Change (ha) between 10%R, LS and 2002 C

Class (ton/ha/yr)	5m RUSLE (ha)	Change in Score (10%R)	Change in Score (10% LS)	Change in score (2002 C)
0.00	813.75	0.00	0.00	-3.98
0-2	7692.60	-324.01	-232.76	-657.91
2-4	1499.25	-60.98	-38.28	240.52
4-6	753.35	93.44	70.55	159.55
6-8	352.22	95.99	67.47	96.89
8-10	171.30	69.17	48.57	58.05
10-12	89.60	41.68	27.60	35.39
>12	165.64	84.72	56.85	70.67
max	1048.34	201.66	119.70	854.89
mean	0.82	0.16	0.12	-0.20

4.3 RUSLE Validation

Validation of models is vital to their success as environmental instruments that can drive landscape understanding and management. To validate the RUSLE model in this study, multiple techniques were used. These include, in situ sample meter testing, particle size analysis, TSS testing, nutrient analysis, field observations and comparisons with other studies.

4.3.1 In Situ sampling results

A field meter with a conductivity probe was used in the field during dry and wet conditions to identify the quantity of total dissolved solids (TDS) and other parameters such as salinity. Figures 15 and 16 show the TDS results of in situ sampling using the field meter. TDS values were measured to provide field proxy for the lab based TSS measure. In both figures, Rocklow and the Lower Minnamurra river had the highest TDS values, occurring 2 orders of magnitude higher than the other measured tributaries. The remaining tributaries show a trend of decreasing TDS moving west in the catchment. There were no noticeable differences between the values measured on the dry vs. the wet day. This would suggest that the TDS content in tributaries is independent of rainfall driven erosion.

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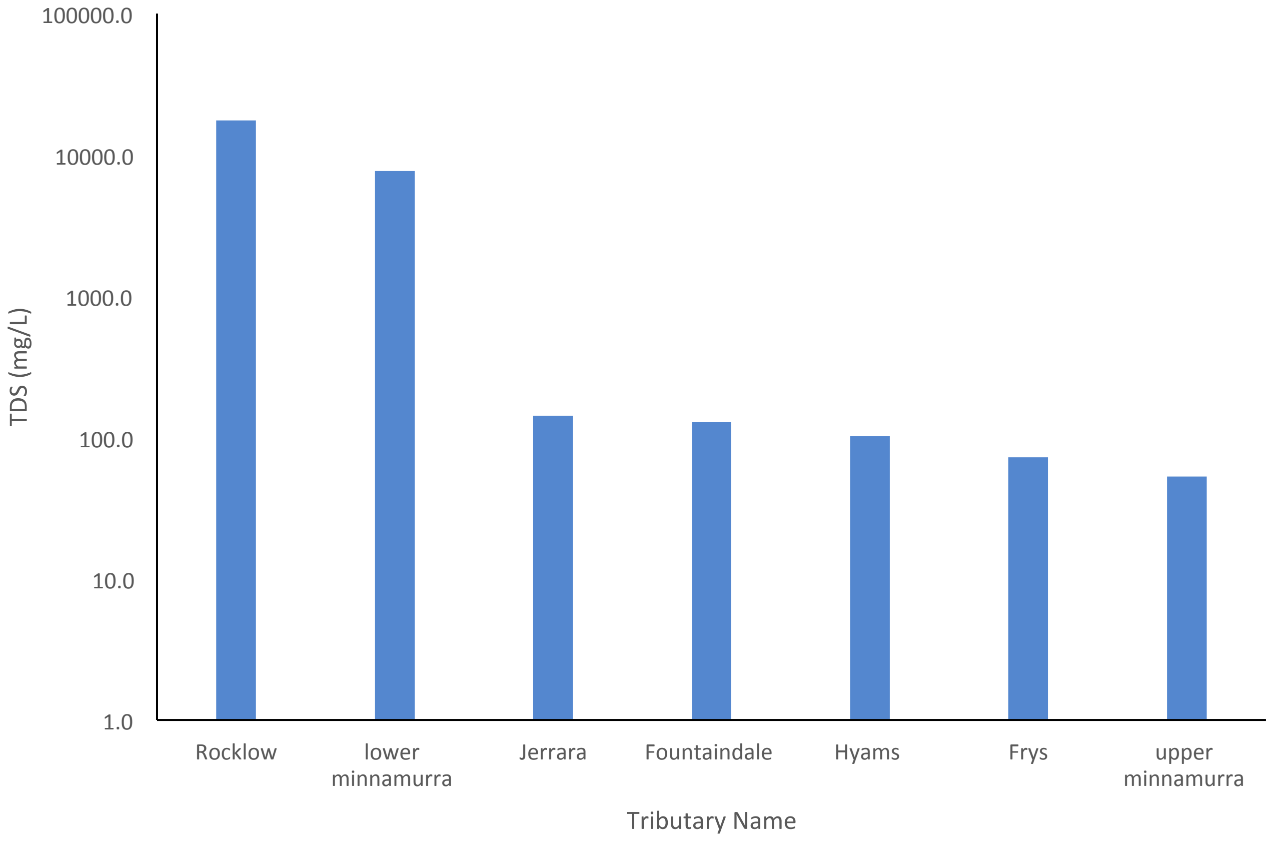


Figure 15 15/08/19 dry sample run values (log_{10} scale)

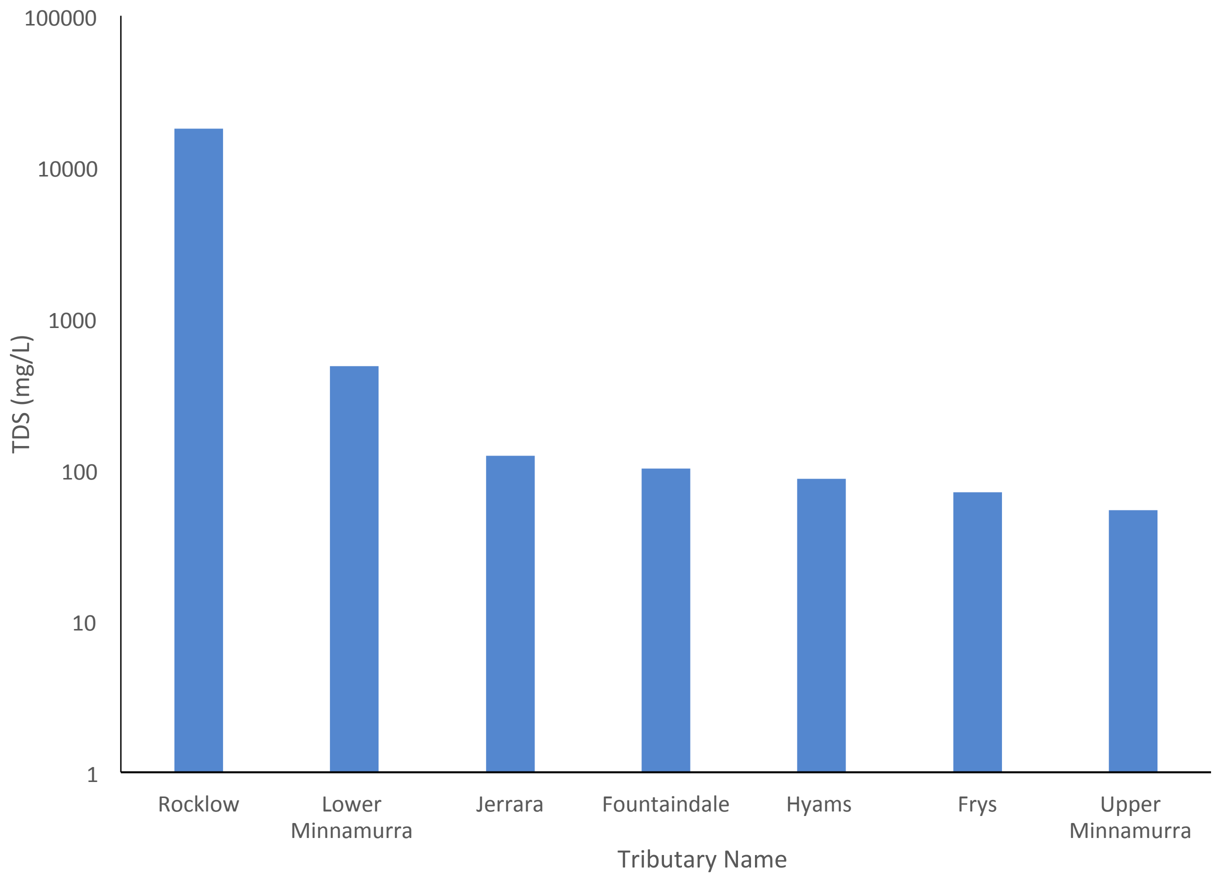


Figure 16 30/08/19 wet sample run values (log_{10} scale)

4.3.2 Particle size analysis

Figure 17 shows the sediment sorting in the 7 flowing rivers during a low flow (LF) sampling period. All locations exhibit a small proportion of clay content. Sand grains are recorded in proportions of up to 48.9% in Jerrara Creek to 2.48% in the Lower Minnamurra river. Silt is the major component in the all samples except for Jerrara Creek which has a 48.9%:47.89% sand to silt ratio. There does not appear to be any clear downstream or upstream patterns in the data. The most notable difference in the data is the small sand value in the Lower Minnamurra river.

In figure 17, particle size is also displayed for a sampling run following a 40mm rain event (HF). Percentages of sand movement are significantly lower than the low flow values, notably Rocklow creek exhibited 0% sand content. The amount of clay particles also increased, in all tributaries with a range of 4.12% (Jerrara Creek)-17.13% (Rocklow Creek). Silt remains the most significant grain size in for the catchment, increasing in proportion from the low flow event, with a catchment mean of 73.17% compared to the mean of 65.95% from the low flow event in figure X6. Similarly, to the low flow event, there is no clear downstream or upstream trends evident in the data.

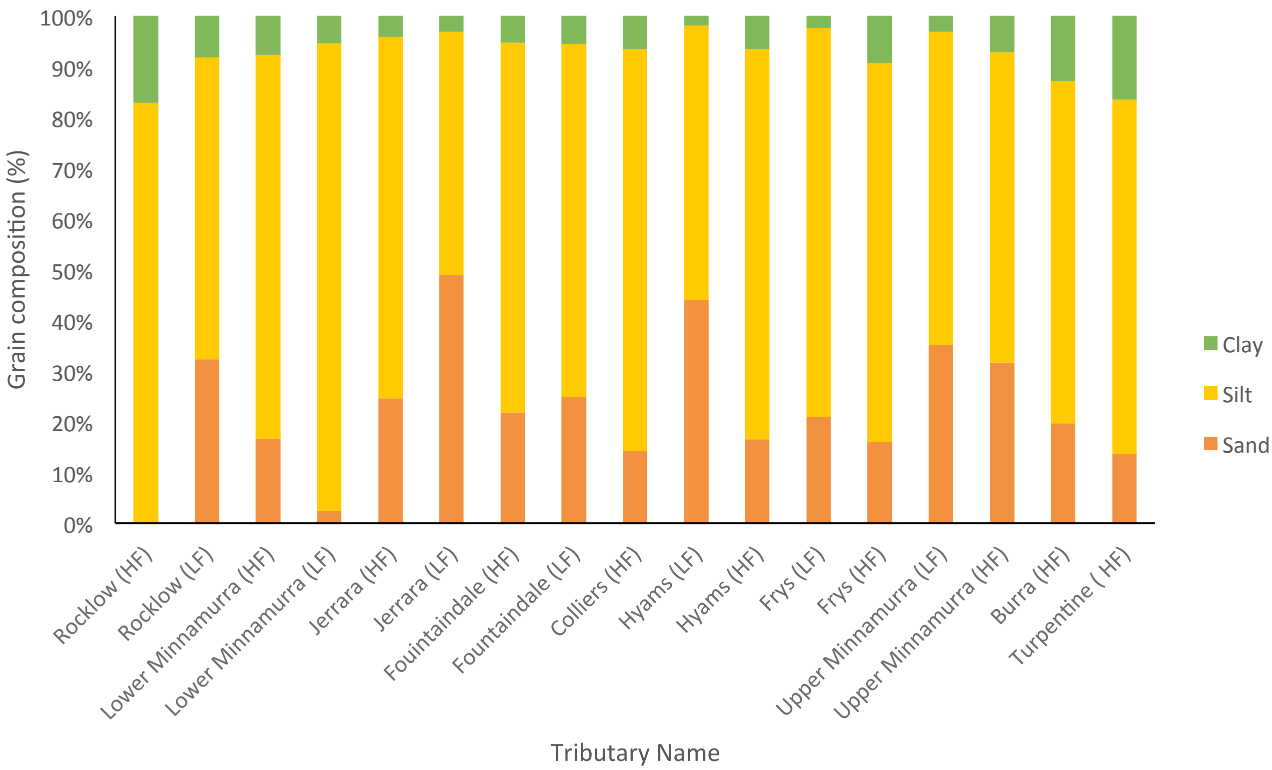


Figure 17 Sediment characteristics for tributaries during high flow (HF) and low flow (LF)

Mean particle was calculated by the mastersizer on both the low and high flow samples, (Figure 18). The results showed a large decrease in particle size from low flow to high flow in Rocklow, Jerrara and Hyams creeks. Less variation occurred in the remaining sample segments and it should be noted that there were only measurements for high flow conditions in Colliers, Burra and Turpentine creeks. The data range in low flow conditions was 46.62μm compared to 25.16µm during high flow. The mean is higher in low flow at 35.29µm where during high flow the mean was 21.16µm.

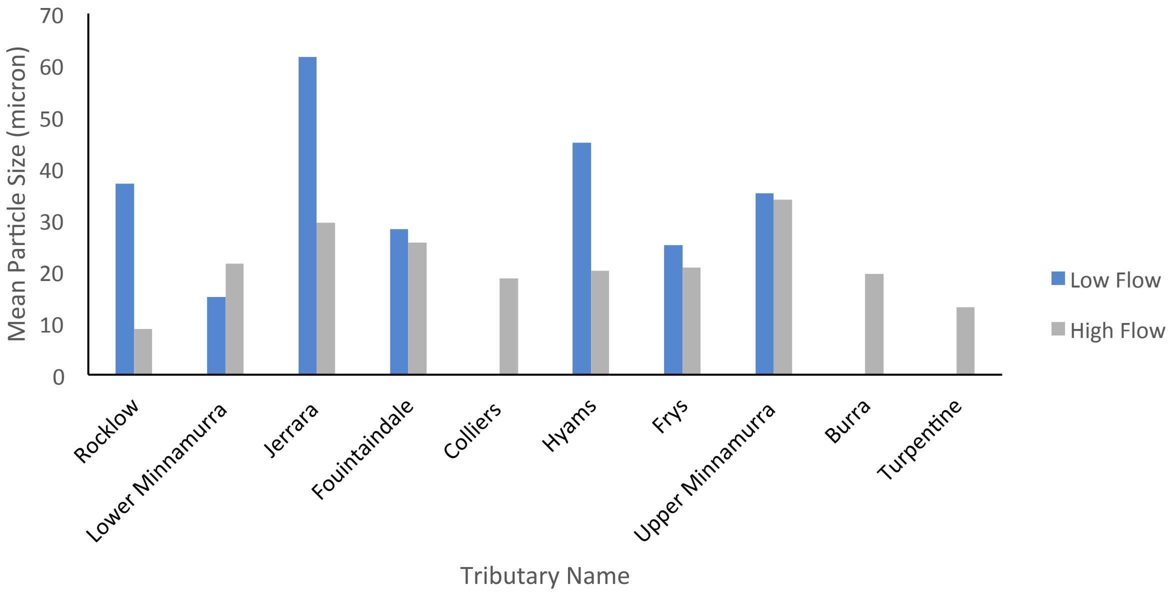


Figure 18 mean particle size (microns) in low and high flow states

4.3.3 TSS

<u>Dry low flow sampling</u>

The results in Figure 19 are from the low flow sampling run, taken after a period of low rainfall on the 15/08/19. The waterway with the highest TSS was Rocklow Creek, with 6.6mg/L, however this is extracted from one reading, as the second 500mL aquilot did not pass the Grubbs test for outliers at >50mg/L. Other creeks with higher relative TSS were Fountaindale, and the Lower Minnamurra river. Hyams, Frys, and the upper Minnamurra River showed very low values, although the filters in the Hyams Creek samples were sediment rich. The TSS mean for the catchment during dry conditions was 4.0mg/L. Overall TSS sampling in dry conditions was heavily restricted by the detection limit of 0.5mg/L.

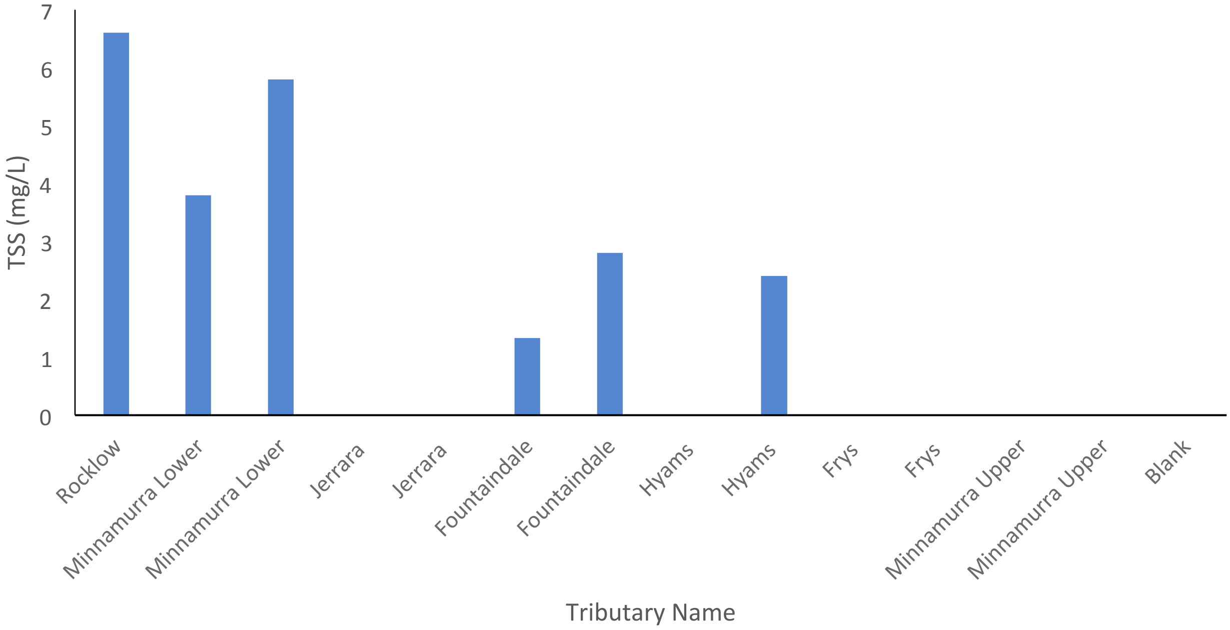


Figure 19 Dry event sampling from the 15-08-19 showing TSS levels (mean) in catchment tributaries

<u>Wet sampling 1</u>

Sampling was undertaken on the 30/08/19 after ~40mm of rainfall over the previous 24hrs. During this sample run Colliers Creek, Burra Creek and Turpentine Creek did not flow. The remaining 7 sample locations were analysed for TSS by ALS environmental laboratories in Wollongong. The limit of reporting of 5mg/L meant that values were only measured for Rocklow Creek (8mg/L), Fountaindale Creek (6mg/L) and Hyams Creek (7mg/L). The remainder of the tributary samples were <5mg/L (Figure 20).

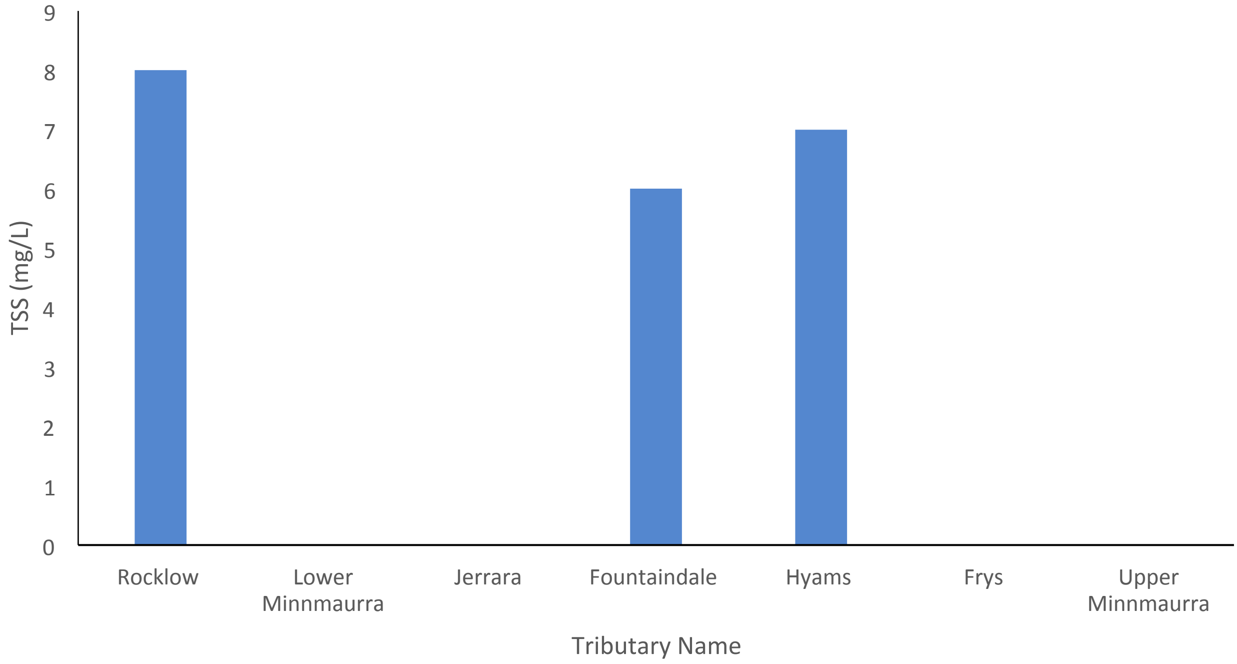


Figure 20 ALS TSS with a limit of reporting = 5mg/L

<u>Wet sampling 2</u>

Wet sample run two was collected on 19/09/19 after ~60mm of rainfall. These samples were taken the day following a rainfall event that effected the entire catchment. Of the 10 tributaries selected for sampling 9 were running on this day, the exception being Turpentine Creek, which showed no signs of flow, however had flowed after a similar event at the beginning of the year. Considering the detection limit of 0.5mg/L, the upper Minnamurra river and Burra Creek did not register significant values. It should be noted that Burra and Colliers creeks become stagnant during dry periods. Figure 10 shows that Fountaindale Creek exhibited the highest amount of TSS after the rain event with an average TSS value of 8.5mg/L. Notably on analysis it was clear that much of the contents here was farmyard organics. The graph also shows that lower catchment tributaries demonstrate higher TSS contents than the upper catchment regions with Rocklow Creek having a mean of 3.9mg/L and the lower Minnamurra with a mean of 3.9mg/L.

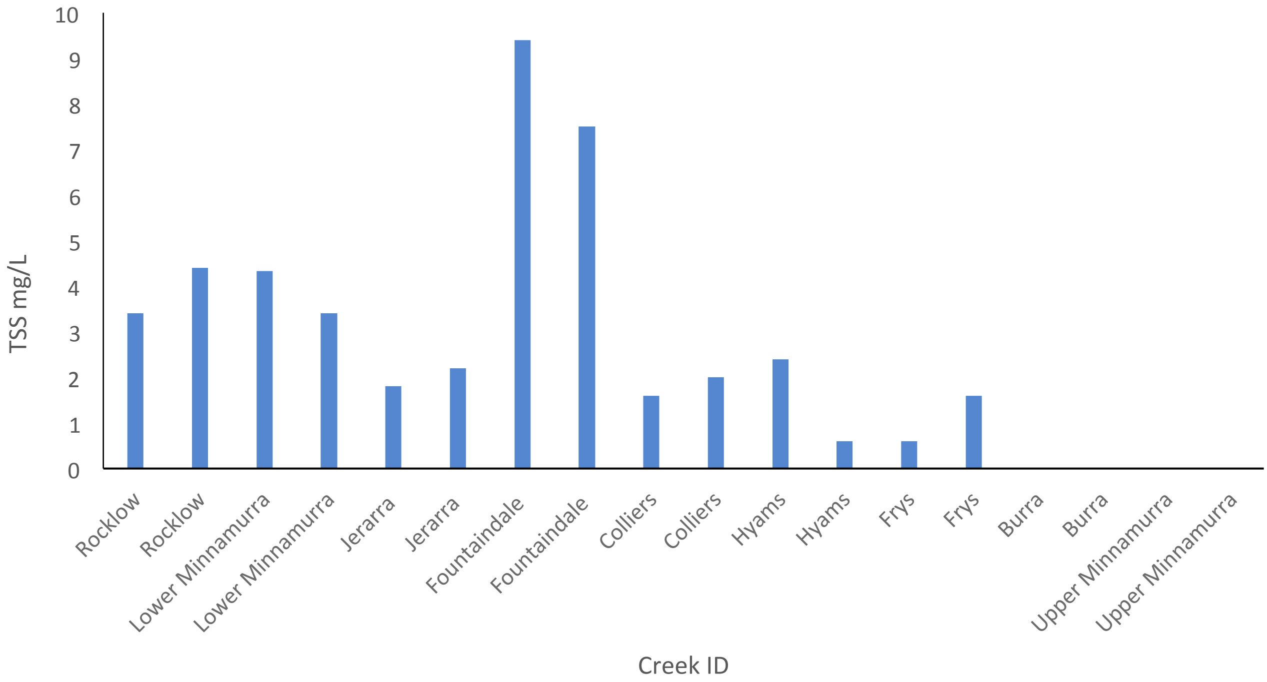


Figure 21 Wet event sampling from the 21-09-19 showing TSS levels in catchment tributaries, samples were taken after a 24hr period of ~60mm rainfall

4.3.4 Nutrient analyses

Nutrients were analysed by ALS laboratories during wet sampling run 1 (see previous heading). Nutrient runoff was measured using calculations of total nitrogen (TN) and total phosphorus (TP). ALS records the LOR as 0.1mg/L. The maximum values recorded for TP and TN were found in the Fountaindale Creek samples (Figures 22 and 23), with 0.13mg/L TP 1.5mg/L TN concentrations. Nutrients were found to be highest in waterways that run their course through a significant amount of pasture/farmland, such as the lower Minnamurra river, Jerrara, Fountaindale, Hyams (farm and residential) and Frys creeks. Rocklow Creek exhibited values of <0.05mg/L in both TP and TN, and the Upper Minnamurra had values of 0.1mg/L TN and <0.01mg/L TP.

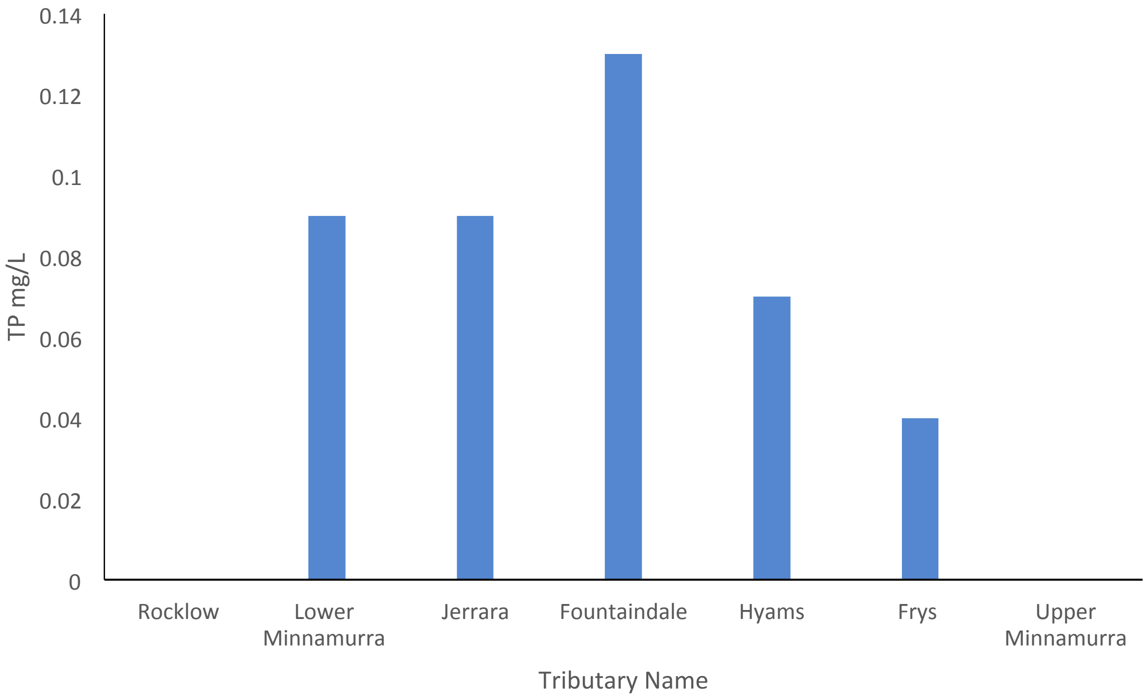


Figure 22 ALS TP results for sampled tributaries

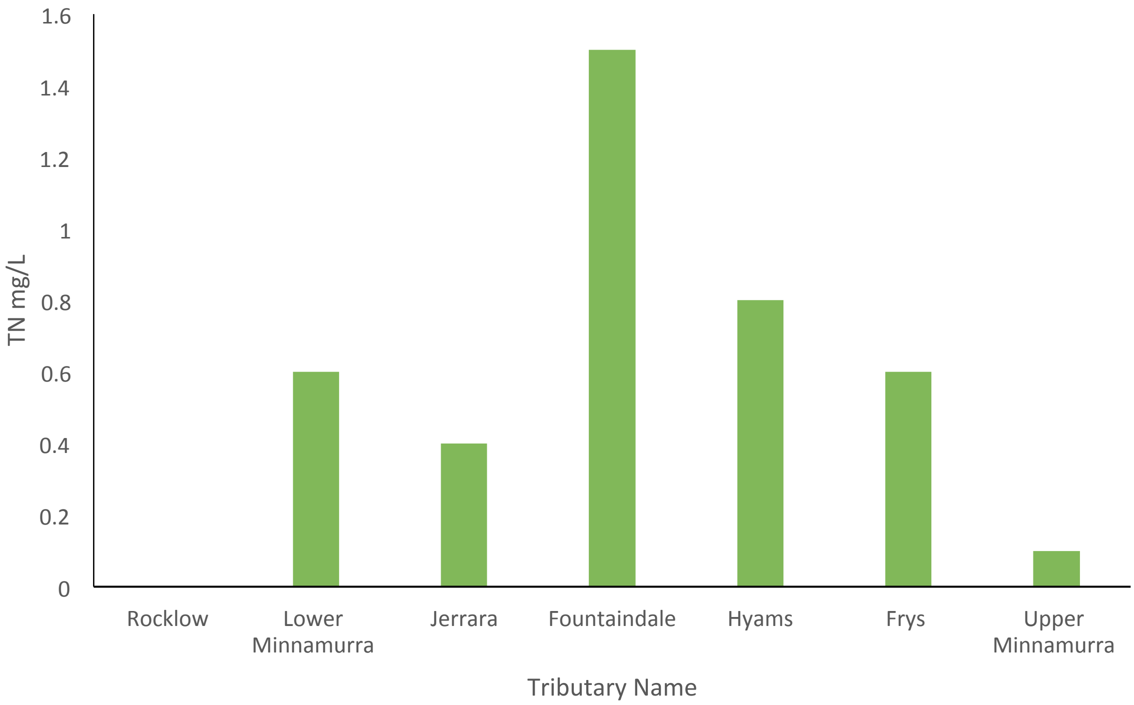


Figure 23 ALS TN results for sampled tributaries

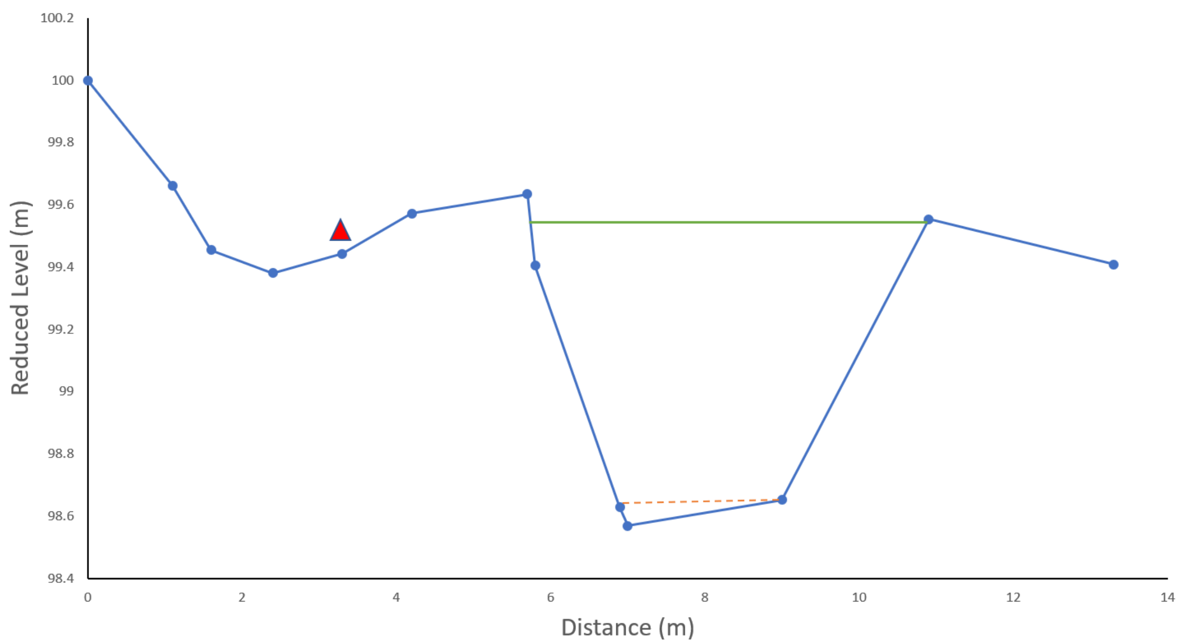
Table 7 ANZECC 2000 trigger values for south-eastern Australia

Table 3.3.2 Default trigger values for physical and chemical stressors for south-east Australia for slightly disturbed ecosystems. Trigger values are used to assess risk of adverse effects due to nutrients, biodegradable organic matter and pH in various ecosystem types. Data derived from trigger values supplied by Australian states and territories. Chl *a* = chlorophyll *a*, TP = total phosphorus, FRP = filterable reactive phosphate, TN = total nitrogen, NO_x = oxides of nitrogen, NH_4^+ = ammonium, DO = dissolved oxygen.

Ecosystem type	**Chl *a***	**TP**	**FRP**	**TN**	**NO_x**	**NH_4^+**	**DO (% saturation)**[l]		**pH**	
	($\mu g\ L^{-1}$)	($\mu g\ P\ L^{-1}$)	($\mu g\ P\ L^{-1}$)	($\mu g\ N\ L^{-1}$)	($\mu g\ N\ L^{-1}$)	($\mu g\ N\ L^{-1}$)	Lower limit	Upper limit	Lower limit	Upper limit
Upland river	na[a]	20[b]	15[g]	250[c]	15[h]	13[i]	90	110	6.5	7.5[m]
Lowland river[d]	5	50	20	500	40[o]	20	85	110	6.5	8.0
Freshwater lakes & Reservoirs	5[e]	10	5	350	10	10	90	110	6.5	8.0[m]
Wetlands	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Estuaries[p]	4[f]	30	5[j]	300	15	15	80	110	7.0	8.5
Marine[p]	1[n]	25[n]	10	120	5[k]	15[k]	90	110	8.0	8.4

4.3.5 Stream Cross-sections

Stream cross sections were created using the dumpy and pole method. Figure 24 shows an example of a typical cross section in this study.



Estimated Bankfull Level (Depth m)	Estimated Bankfull Width (m)
1.1	5.30
Bankfull Cross Sectional area (m^3)	Velocity (m/s) [Float method wet conditions]
5.83	0.16
Bankfull Discharge (m^3/s)	
0.9328	

Figure 24 Hyams Creek cross section. The red symbol represents the location of the dumpy level, the dotted line is water level on the day of site visit, and green representing the bank full height. The table shows the calculated parameters

Flow velocity was able to be measured in five out of ten sampled tributaries. This was a factor of irregular flow patterns, such as Fountaindale and Colliers Creek eddies and snags. Table 8 shows the bank full discharge and flow velocities for the measured locations. The table shows that the highest discharge is found in the upper Minnamurra river, followed by Frys Creek and the Lower Minnamurra river. Rocklow and Hyams creeks display low discharge values due to mild topography and small cross-sectional areas. In Table 8 the sediment yields were calculated in kg/day. They showed that the Lower Minnamurra river has the highest estimated sediment yield out of the five locations sampled (2,558,283kg/day). The upper Minnamurra river despite having the highest discharge, does not have an accurate measure for sediment yield as the TSS samples were below the measurement threshold of <0.5mg/L.

Table 8 sediment yield a bank full flow in measured water ways

	Discharge m^3/sec	discharge L/day	Wet sample TSS kg/L	Sediment yield kg/day
Rocklow	1.0	87,477,667	0.0078	682,325
Lower Minnamurra	4.1	350,449,804	0.0073	2,558,283
Hyams	0.9	80,593,920	0.003	241,781
Frys	5.9	510,332,659	0.0022	112,2731
Upper Minnamurra	20.7	1,786,019,674	0	0

4.3.6 Field observations

Bank trampling

Bank trampling was observed in the catchment in some of its creeks. Creeks of note include Hyams Creek (shown in figure 25), Fountaindale Creek, Burra Creek, Turpentine Creek, and Frys Creek. It is likely that other creeks in the study experience a degree of bank trampling, however it was not directly observed in the field. In all cases the result of cattle access to the creek bank was a loss in bank vegetation, soil compaction, soil exposure and cattle faeces. The bedload rocks of Fountaindale Creek are lined with an organic film, which is likely the result of high nutrient loads into the tributary.

Figure 25 Cattle near the banks of Hyams Creek, with clear trails leading towards the water's edge and up the slope in the background

Although Turpentine Creek was only observed flowing during one period of the study there is evidence to suggest that mass amounts of sediment are moved from this section of the catchment. Figure 26 shows a site in the Curramore sub-basin where mass movements of bank sediment have occurred, and the exposed soils and undercut tree roots suggest that this area continues to be unstable. It's also worth noting that this site suffers from a lack of riparian vegetation, cattle trampling and steep slope factors, which would contribute to the feature. The DEM derived cross section of the bank shows an approximate 2m elevation difference from the inner bank to the damaged outer bank.

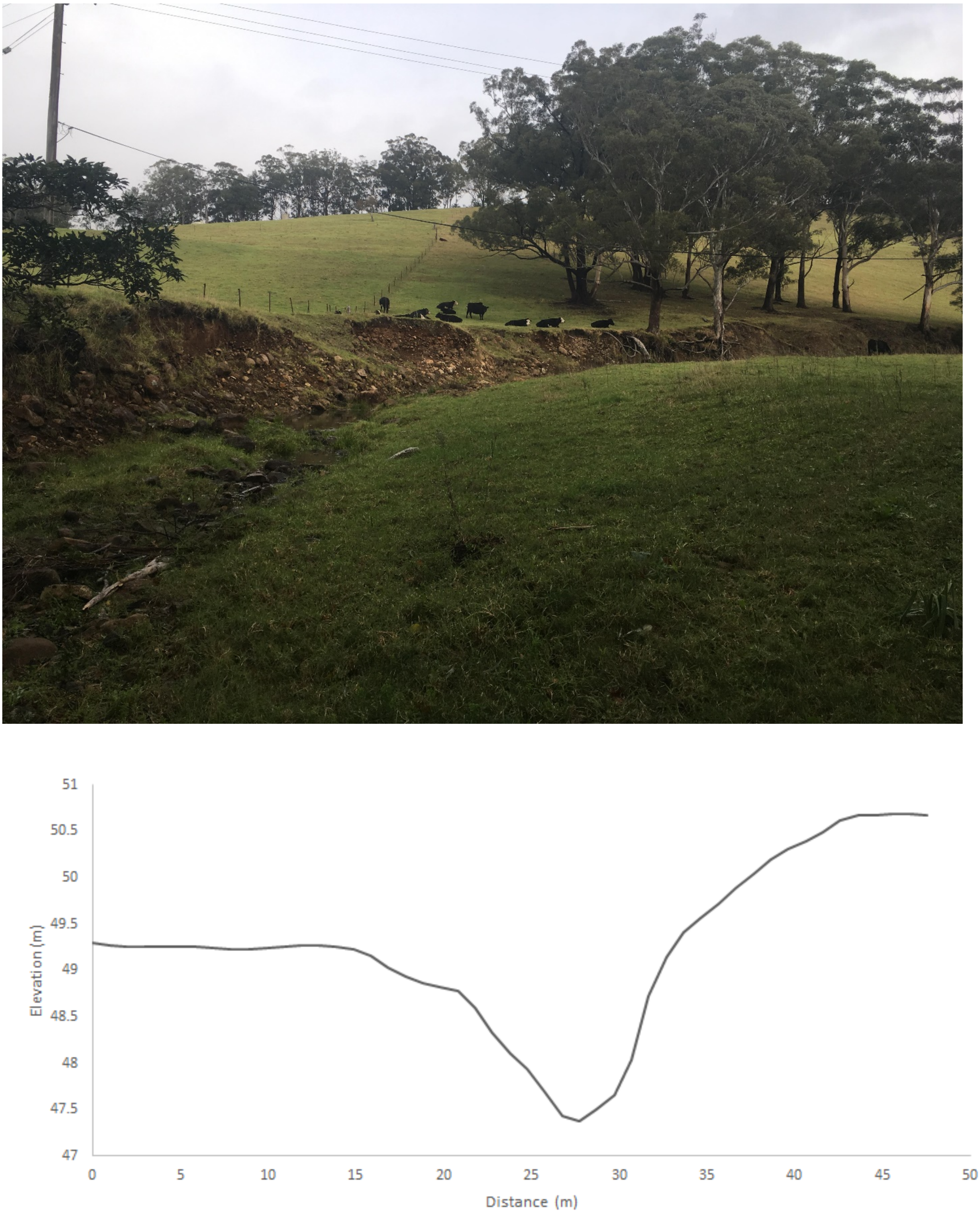


Figure 26 A significant bank erosion site located in the upper section of Turpentine Creek accompanied by a DEM derived cross section of the bank.

4.4 Model Comparison

The OEH has undertaken a broad scale application of the RUSLE model, covering the state of NSW. This output was clipped to the catchment limits of the Minnamurra river catchment as seen in figure 28. In this figure the highest values for hillslope erosion occur high in the catchment, where slope is at its maximum. This trend was also observed in the higher resolution RUSLE in figure 27. The key difference, however, is that rainforest and native hillslope vegetation covered in the C factor has a greater influence on the upper catchment regions than in figure 28. The coarseness of the C, K and R factors in the OEH RUSLE limit the usefulness of state wide studies on the catchment scale, however the values that it does present can be used to assess how much influence these factors have over the LS factor when high resolutions can be achieved.

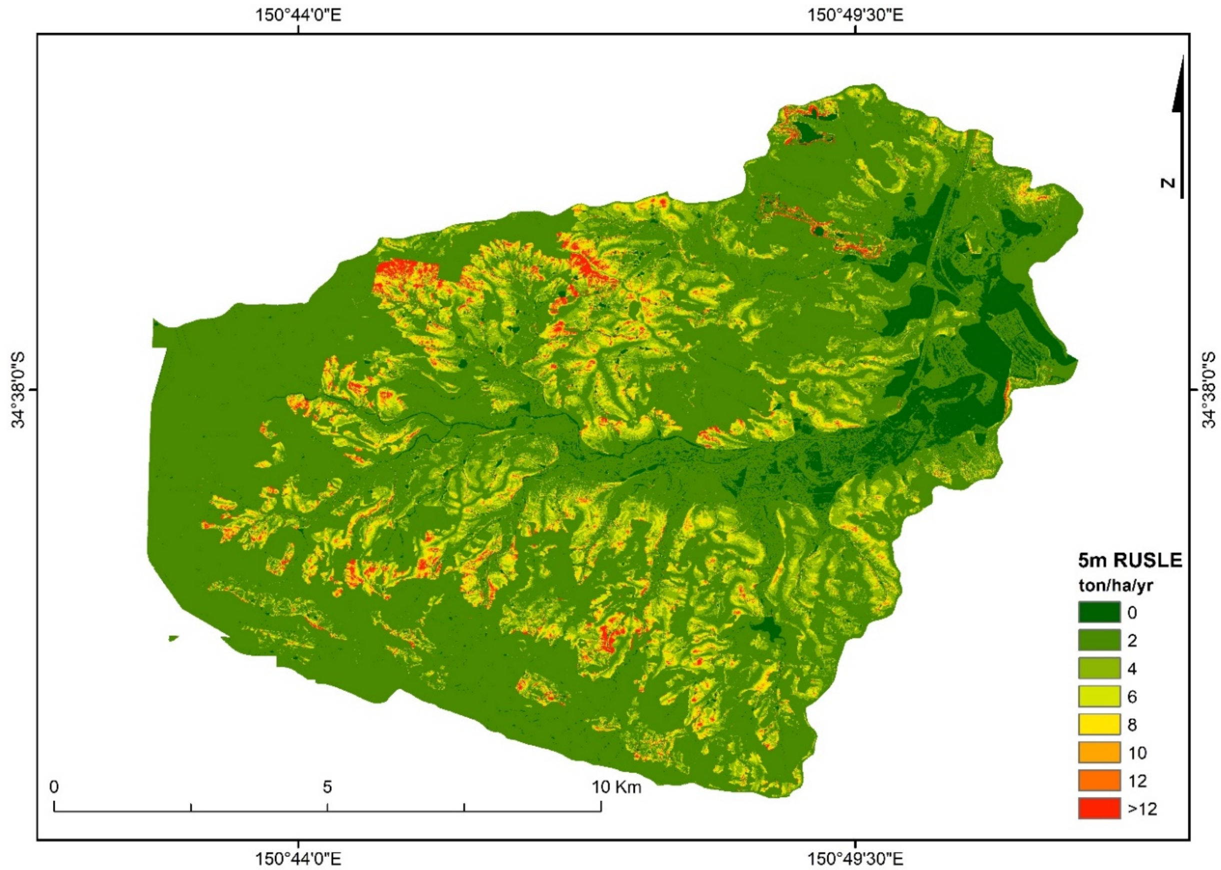


Figure 27 5m RUSLE output, developed in the current study

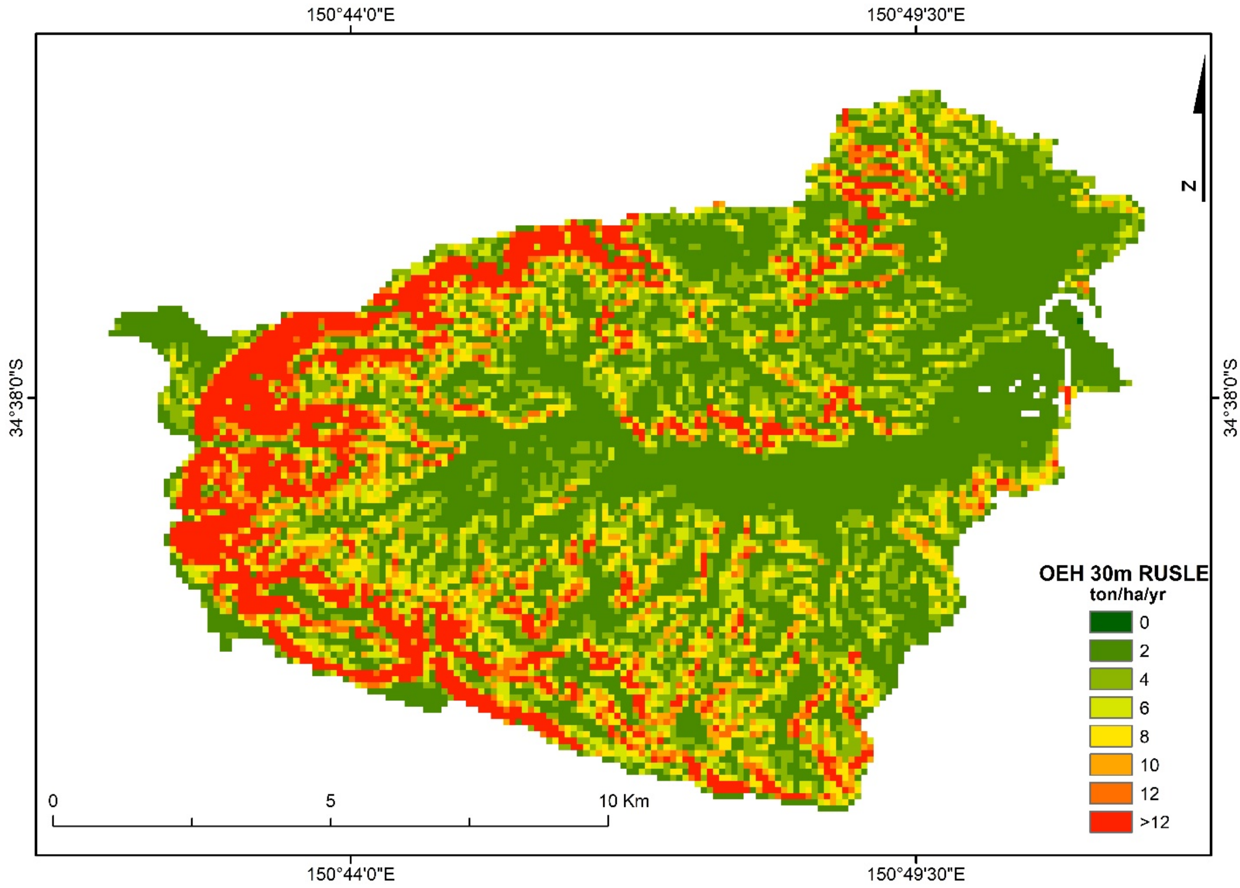


Figure 28 OEH derived 30m resolution RUSLE

The OEH used the PERFECT model to create a simulation of TSS distributions in the Minnamurra river catchment. The trends produced by these models are represented in figure 30. The map reveals that the main areas of peak TSS occur in the Curramore region which includes Turpentine Creek. Peaks also occur at the headwaters and lower reaches of Rocklow Creek, and around the tidal limit of Minnamurra River, including Jerrara Creek. Figure 29 displays the zonal mean values for hillslope erosion for the catchment, thus providing a simplified spatial representation of the trends seen in figure 27. Figure 29 shows that there is high erosion occurring at the headwaters of Turpentine Creek, and Rocklow Creek, Jerrara, and Hyams creeks. The data trends would suggest that were the RUSLE model shows areas where erosion occurs initially in the catchment, where TSS modelling becomes an indication of where the resulting sediment accumulates.

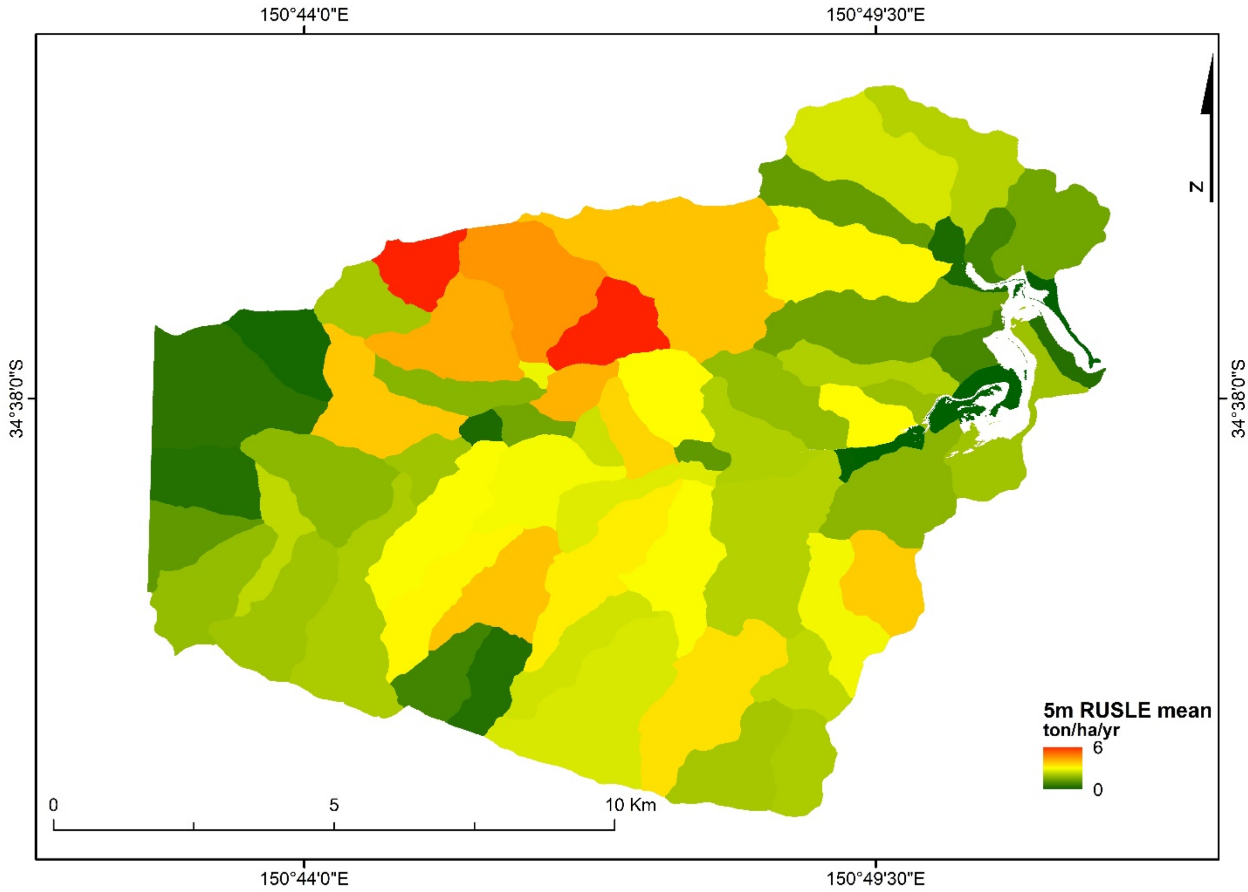


Figure 29 Mean zonal statistics map derived from figure 12X data and OEH sub basins

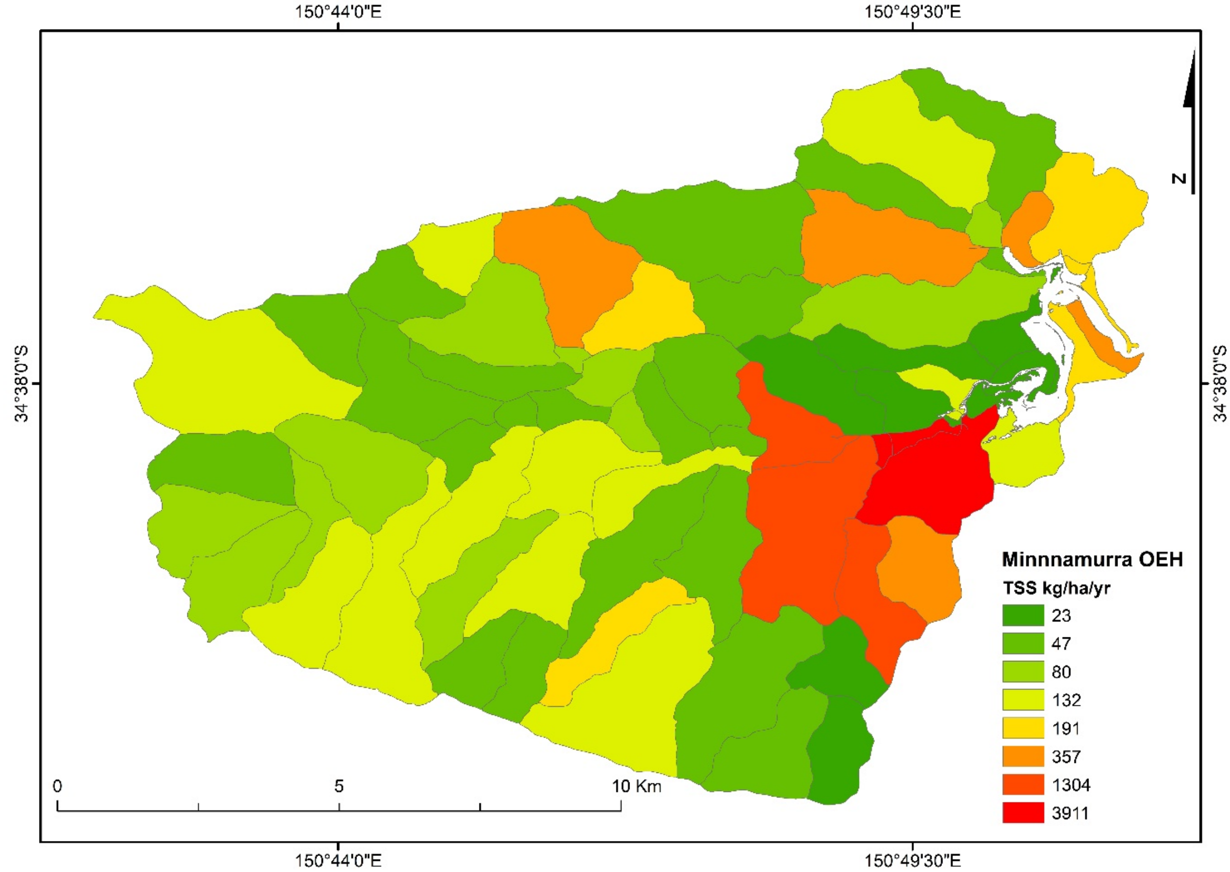


Figure 30 OEH TSS data, vector format

Nutrient Analysis and OEH TN and TP models

Figures 31 and 32 show the trends in nutrients modelled by the OEH. The major nutrient rich region occurs in the Jerrara and Lower Minnamurra (tidal limit) area of the catchment, with some significant nutrient values occurring in a mid to lower Rocklow Creek sub-basin. These maps were analysed in conjunction with the TP and TN values measured by ALS laboratories (see figures 22 and 23 under heading 4.3.4). While the laboratory sampled values do show that the lower Minnamurra river and Jerrara Creek exhibit some TP and TN enrichment, most of the enrichment is seen in Fountaindale Creek. The model does show that a moderate level of nutrients occurs in the upper reaches of Fountaindale Creek but not to the extent of enrichment measured in the field. Site walks of Fountaindale Creek indicated that Fountaindale Creek suffers from significant bank trampling through cattle access and thus the agricultural sediments observed in the river are higher than a spatial model could simulate.

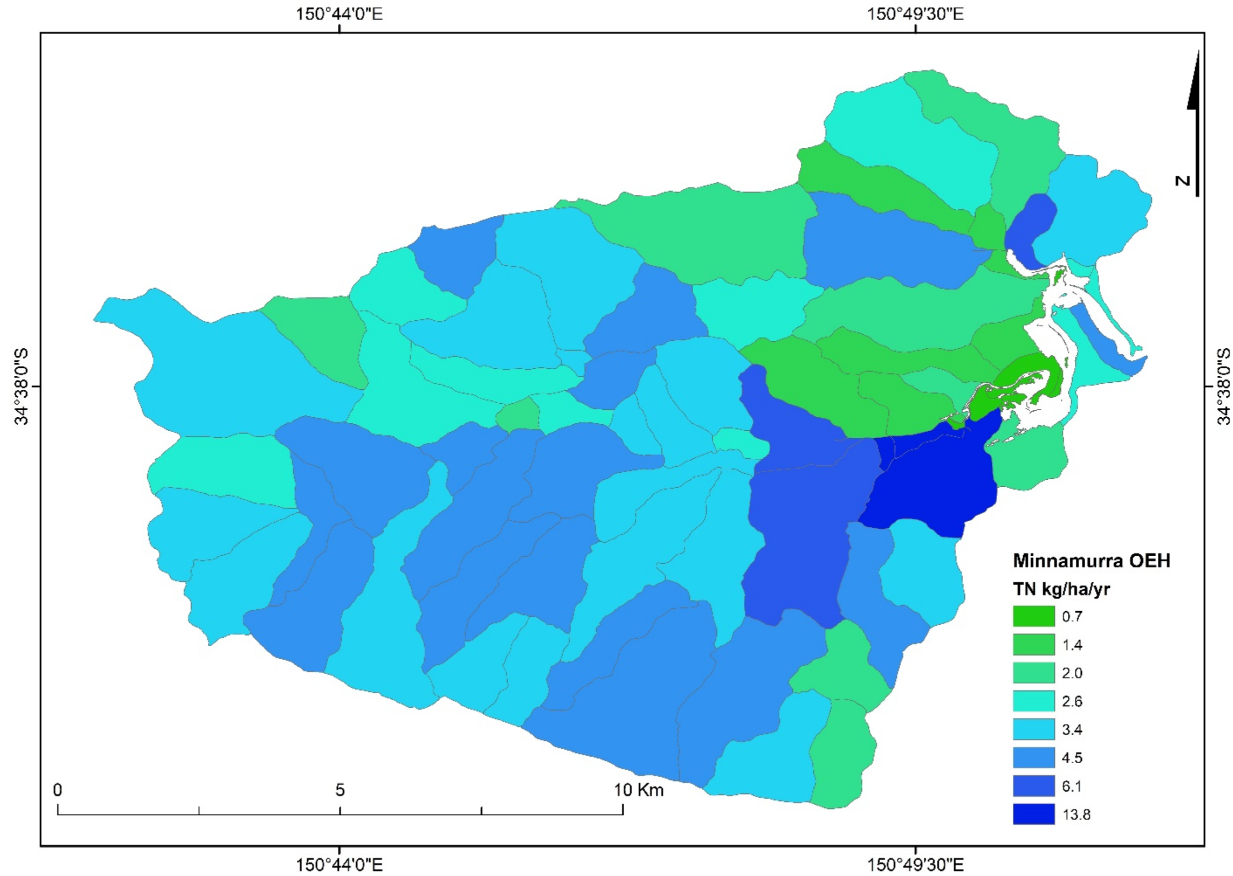


Figure 31 OEH TN distribution within sub basins

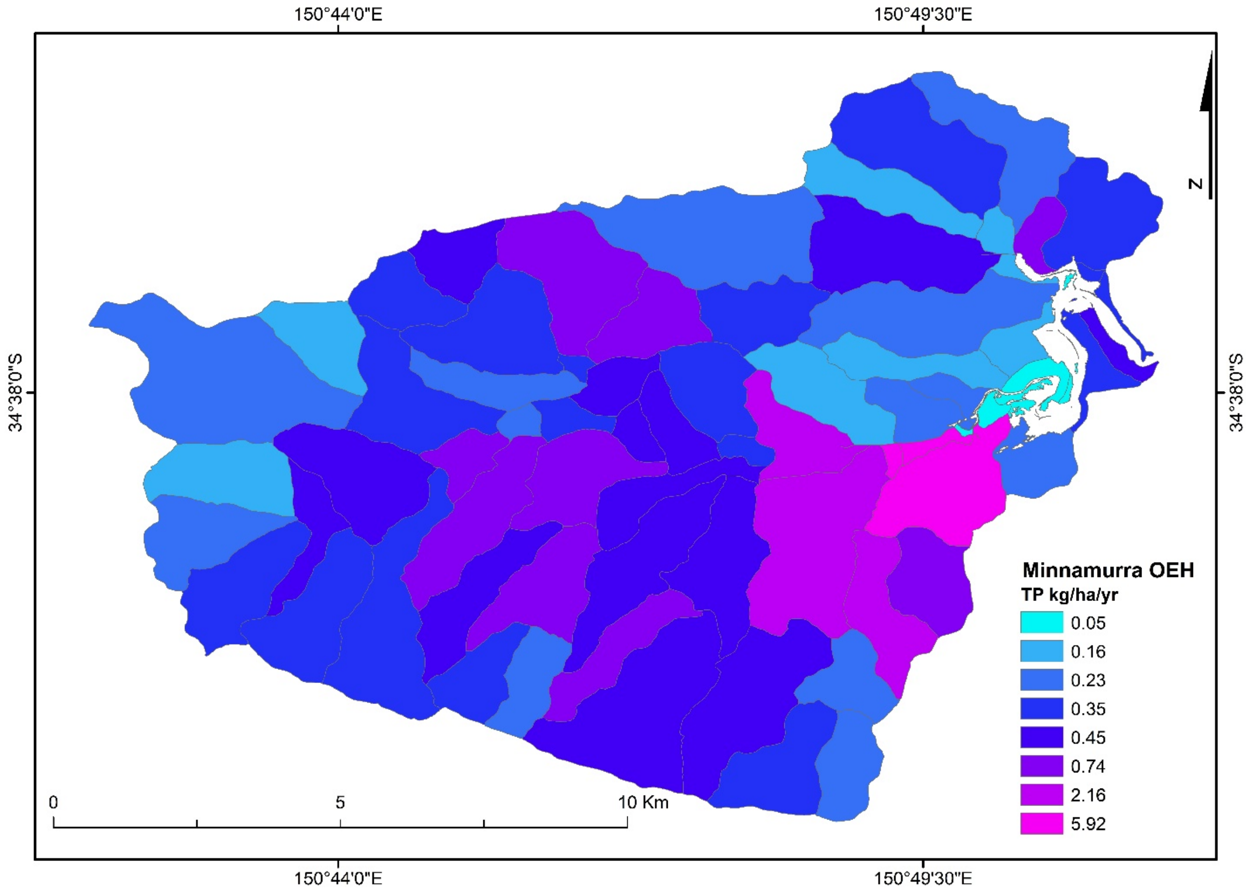


Figure 32 OEH TP distribution within sub basins

6 Discussion

In this chapter the results of the application of the RUSLE model on the Minnamurra river catchment are interpreted. The output of the RUSLE will be discussed, followed by a dialogue assessing RUSLE validation methods. To provide further understanding on how the RUSLE functions the sensitivity of each factor will also be explained in detail. Site specific conditions that were not represented in the RUSLE will be mentioned, leading into the recommendations of the study.

6.1 Application of RUSLE at Minnamurra

The Minnamurra river catchment covers 115km^2, with forested uplands and agricultural lowlands. This was pre-dated by basin wide forests and swampland prior to European land clearance and floodplain draining. The application of the RUSLE model acts as a preliminary study on the erosion trends that exist in the catchment, in its current form as a small farming region, with some mining influence. The RUSLE model was successfully applied to the Minnamurra river catchment and consisted of detailed layers representing, rainfall erosivity, topography, soil erodibility, and landcover. The model showed that most of the heavily eroding sections of the catchment occurred on hillsides, with the notable exception being the Dunmore Quarry site. Low elevation regions such as the floodplain exhibited very little erosion. The well forested upper catchment, including areas such as the Minnamurra rainforest are some of the steepest areas of the catchment as seen in the LS factor. These areas did not exhibit heavy erosion however, due to the low C factor assigned to them, as native woodlands provide excellent erosion protection. Other sections with lesser slopes eroded more, such as the Turpentine (Curramore) sub basin.

The result in the RUSLE model is the product of the four factors used to create the model. Sensitivity analysis which is elaborated further under heading 6.3 showed that the RUSLE is most sensitive to the R factor, however this factor does not explain the spatial variation of erosion in the catchment. The spatial variation and resulting areas of high and low erosion are best explained by the C and LS factors. The K factor has the lowest weighting in the calculation, and this is due to the limited resolution data available for soils. The K factor if studied in detail would be highly variable as a result of management factors such as soil disturbance and change in organic contents, however this would require extensive catchment wide studies to calibrate (Lu et al., 2003). As such the K factor extracted from the 1:100,000 soils sheet is the most limited component of this studies RUSLE (Hazelton 1992)

The RUSLE output suggests that the sub basin that drains into Fountaindale Creek should not be particularly erosive. The field data however suggests otherwise, as this creek exhibited the highest values for TSS, as well as TP and TN. This is likely due to the shortcomings of the C factor, as the RUSLE does not consider the protection provided by riparian vegetation. Fountaindale Creek exceeds the default low risk trigger values for TP and TN in the ANZECC guidelines (Table 7). Other tributaries in the catchment exceed the trigger values, such as Hyams Creek with >0.06mg/L TP and 0.8mg/L TN, however Fountaindale Creek exceeds these values by over 2 times the trigger value with 0.13mg/L TP and 1.5mg/L TN. While these values may not pose a serious issue in the present, to avoid potential ecosystem disturbance in the creek these values should be addressed (ANZECC 2000)

Major peaks in hillslope erosion values occur in the Curramore region (Turpentine), Dunmore mine site (Rocklow) (Figure 1). Both areas have significant slope and rank high in the C factor. The quarry is essentially exposed sediments laying on a hillside, which would result in large values in the RUSLE. It should be noted that the RUSLE does not consider the control practices that are put in place by the quarries themselves and simply assumes that the area is a bare hill. Minor hotspots occur in Hyams and Jerrara creeks. The trend is that these areas are typically less vegetated than similar slopes such as those found in the Frys Creek sub basins (Figure 10). Figure 11 and 13 shows that most of the erosion is occurring in the north and south of the catchment, with the well vegetated western upper catchment (west) and the flat lower catchment (east) showing the lowest erosion. Broadly this indicates that erosion occurs on hillslopes that have an element of clearance, where landcover does not provide adequate protection from rainfall erosivity.

There have been several Australian based studies that have used USLE based models to assess erosion rates in Australia. The RUSLE has been used to measure soil erosion for the whole continent by Lu et al (2003) and for the state of New South Wales referred to in chapter 5 by Xihua Yang and the OEH(Yang 2014; Yang 2015; Yang and Yu 2015; Yang et al., 2018). The continental average soil erosion estimated by the RUSLE equation is 4.1 t/ha/yr, with the highest erosion occurring in the North of the continent (Yu et al., 2003). In contrast the mean hillslope erosion modelling in the Minnamurra catchment in this study is 0.82 t/ha/yr. This can also be compared to the New South Wales OEH RUSLE clipped to the Minnamurra catchment, which displays an average value of 5.2 t/ha/yr. Higher resolution catchment studies that focus on south eastern Australia tend to have lower mean erosion, with losses of >10 ton/ha/yr considered very high erosion (Erskine 2002; Simms 2003; Martinez 2009). Even with improved data sets for catchment-based study, USLE based models do tend to overestimate erosion rates when compared to ^{137}Cs dating measurements, reporting up to 10 times overestimation when using the SOILOSS model by Martinez (2009). Precision modeling therefore requires extensive calibration with environmental measurements (Simms 2007).

The RUSLE model applied to the Minnamurra catchment provides an estimation of erosion trends and erosion rates in the region. When compared to other available data for these estimations, the model shows improvement in reporting, when compared to low resolution applications of the RUSLE model and comparable results when referring to similar scale studies. The limitations of RUSLE to account for intricate features such as riparian vegetation should be noted and could account for the anomalous values found in Fountaindale Creek. The model is a best estimate of hillslope erosion, further calibration would improve this (Wischmeier and Smith 1978).

6.2 Accuracy assessment of RUSLE

A model such as the RUSLE cannot be utilised confidently as a management tool unless it is supported by an accuracy assessment (Wischmeier and Smith 1978). To provide validation in this study three main methods were used, these were water quality analysis, sediment discharge estimation and a model comparison.

A common validation of erosion models such as the RUSLE is the use of sediment yield data. Sediment yield is the downstream trend of hillslope erosion, and thus having a detailed data set of sediment yield rates and historical deposition amounts is a simple form of validation (Van Rompaey et al., 2003; Simms 2007). This method requires a closed system in order to measure sediment yield directly. This was not possible in many open catchments such as the Minnamurra River, providing a limitation of data availability (Benavidez 2018). To mitigate this limitation total suspended solids (TSS) were assessed in place of sediment yield. TSS field analysis validated the rainfall response, as TSS was highest for all tributaries under rainfall conditions, as expected. TSS was also highest in Rocklow and the Lower Minnamurra river. In the case of Rocklow Creek this can be attributed to the influence of the Quarry which is indicated as a 'hotspot' of erosion in the RUSLE. The high values in the lower Minnamurra river sample can be interpreted as a representation of catchment scale processes, as all major tributaries excluding Rocklow contribute to the main river at this sample location. Mid catchment streams such as Jerrara, Colliers, and Hyams Creek all exhibit mild TSS loads, which is representative of the RUSLE, which also presents these areas are low to mid-range erosive areas. Frys, Burra and the upper Minnamurra River have the lowest TSS values in the catchment. This provides support for the erosion protection provided by the well vegetated uplands of the catchment's Western slopes. TDS field measurements using the conductivity probe support this analysis as Frys Creek and the Upper Minnamurra river also exhibit the lowest values here. Rocklow and the Lower Minnamurra river had very high TDS values, which as due to the influence of tides, which bring with them ocean based dissolved solids with associated high salinity.

A particle size analysis was undertaken to provide an extra level of validation to the TSS and TDS measures. The results showed not clear trend as mean particle size varied throughout the catchment. Interestingly the higher mean particle size in most samples occurred in low flow samples rather than high flow samples. This is the inverse of the expected trend, where higher flow results in increased shear strength which mobilises larger sediments (Bierman and Montgomery 2014). This particle size result is likely due to the low levels of sediment available for analysis and the probability that the larger particles in low flow samples were organic. Cross sections were also a part of this study aimed at providing a more detailed display of the sediment distribution trends in the catchment. Without the aid of a flow meter the float and stick method of estimating river velocities was hindered by snags and low flow rates. As a result, only 5 locations were able to be sampled. These locations were Rocklow Creek, the Lower and Upper Minnamurra river, Hyams Creek and Frys Creek. Of these locations Rocklow Creek and The Lower river had the highest sediment yields with 682,325kg/day and 2,558,283kg/day for high flow periods. Although limited by the amount of sediment yield values estimated, the results do show that TSS and sediment yield are highest in the lower regions of the catchment, which does support the notion that TSS represents the downstream effects of hillslope erosion. Thus, with a more comprehensive study of sediment yield aided by the use of stream gauges the RUSLE could be more accurately validated.

The RUSLE model was also cross validated with erosion, sediment and nutrient transport models created by the OEH. This included a statewide application of RUSLE using a 30m DEM, NSW soil database, rainfall grids and a MODIS imagery derived cover factor (Yang 2014; Yang 2015; Yang et al., 2018). The RUSLE put together in this study does not compare satisfactorily to the OEH RUSLE (clipped to the Minnamurra catchment), with catchment wide erosion means of 0.82ton/ha/yr and 5.2ton/ha/yr respectively. What the comparison does reveal however is that the C factor in catchment scale analysis of RUSLE is more appropriately weighted than in larger scale studies. This assessment is supported by the low values for TSS found is the upper reaches of the Minnamurra catchment where native vegetation is providing a significant amount of erosion protection. The RUSLE model was also compared to TSS simulations undertaken by the OEH in a risk assessment study (Dela-Cruz et al., 2019). The results from the OEHs modelling was sub basin TSS in kg/ha/yr, when related to the RUSLE model it reveals that there is TSS hotspots estimated for Rocklow Creek and Curramore Creek, however the major hotspot occurs around Jerrara Creek and the Lower Minnamurra. This does not directly provide validation to the RUSLE model however it could be representative of the downslope trends of hillslope erosion.

Using available information and collected data the RUSLE model applied to the Minnamurra River catchment has been validated. The comparisons made with TSS field measurements provide adequate validation of the RUSLE and is further supported by TDS measurements. The high Fountaindale Creek values can be explained by site specific factors however results like this do suggest improvements in data resolution could improve model functioning, namely improvements in the C factor calculations. Boggs et al (2002) used TSS gauging stations to assess a simple form of the RUSLE termed rapid based assessment. Cross validation is also well used, however for this study the lack of comparable studies which cover the Minnamurra catchment is limited (Panagos 2015). Other studies have used more sophisticated methods such as Caesium-137 and Lead-210 dating to validate their models, which have had variable results (Lu et al., 2002; Simms 2007).

Poor validation was noted for the values observed in the Fountaindale Creek water quality samples. This is theorized to be due to site specific factors influencing the result, which is elaborated under heading 6.4.

6.3 Sensitivity of RUSLE to parameters

The results of the sensitivity analysis showed that the RUSLE model is more sensitive to changes in the R factor than the LS factor. When compared to other studies such the NSW erosivity mapping undertaken my Yang (2015) the R values are high. For example, the highest value for the upper Minnamurra catchment is 8866 MJ/mm/ha/yr, which is calculated for single station data, the value calculated for Robertson township by Yang (2015), is 4548.4 MJ/mm/ha/yr. This has been attributed to be due lower precipitation values in the interpolated gridded rainfall layer for the state used in the Yang (2015) study compared to the three-station based interpolation undertaken in this report (Yang, pers comm 2019). When precipitation is increased by 10% the values of the final RUSLE input increase. In terms of area change the RUSLE class indicating very high erosion (>12ton/ha/yr) increases by 84.72ha and the mean increases from 0.82ton/ha/yr to 0.98ton/ha/yr. In contrast the highest class (>12ton/ha/yr) when using the 10%LS factor increased by 56.85ha and had a mean erosion value of 0.94ton/ha/yr.

While changes in the R factor inputs do result in the most amount of change in value for the RUSLE, it is also a very homogeneous layer which only varies from east to west in the catchment. The LS factor in comparison is spatially heterogenous and thus is a better representation of catchment characteristics than the R factor which is only based on 3 weather stations in this study. Thus, the spatial variation of high erosion areas such as the Curramore sub basin are better represented by the LS topography factor, defining the layers importance beyond the sensitivity values produced.

Like the K factor the C factor is created using a nominal value weighting approach. The values used are representative of the landcover of the south coast of New South Wales (Rosewell 1993). The significance of the C factor is that it represents the factor that can be altered by humans (Renard and Ferreira 1993). This can be in the form of habitat rehabilitation programs that seek to restore the natural canopy cover of a region or they can be negative changes such as land clearance. In comparison the remaining factors, K, LS and R remain static features that are out of direct human control. While a direct sensitivity analysis could not be carried out for the C factor, the 2013 defined landcover layer was compared with the 2002 landcover layer. This was done to assess how much erosion change occurred in a decade, and how much an altered land cover layer would change the RUSLE output. The results showed that most of the RUSLE class area shifted towards mid-range erosion, with the 2-4 and 4-6ton/ha/yr classes increasing by 240.52ha and 159.55ha respectively and a decrease in the 0-2ha class of 657.91ha. This was due to overestimated of forest cover in the 2002 landcover layer which was delineated with 1:25,000 scale aerial photography rather than 1:10,000 photography used in the 2013 layer. This result shows the importance of high-resolution mapping of the C factor, in order to maintain the integrity of landcover classification (Yang 2014). Only the highest resolution layer is valid, meaning that to compare changed in cover over longer time periods the same map scale and resolution would be required, which is a challenge when historical data is limited.

6.4 Influence of small-scale processes or site-specific factors

Even at high resolutions, models cannot account for every factor that occurs on the land surface. In this study there were some results that did not effectively validate the model, specifically the high TSS and nutrient results Fountaindale Creek. The lack of flow in Turpentine Creek was also a limitation to validation, especially since the RUSLE model suggested this area was particularly vulnerable to erosion.

Small-scale factors and site-specific factors in this study refer to measures that were observed in the field but were not displayed in models. This helps to explain the anomalous trend found in in the Fountaindale Creek samples. In comparison to other creeks in the region, the cattle at the sample location have easy access to the banks, and further up the creek riparian vegetation is poor. The spikes in TSS, TN and TP in Fountaindale Creek support this assertion. Fountaindale Creek exceeds ANZECC trigger values for both TN and TP and exhibits TSS values of 8.5mg/L, double that of the next highest creek with 3.9mg/L.

The Turpentine/Curramore catchments were labeled as hotspots in the RUSLE analysis, however these waterways did not flow under >40mm rainfall. This may suggest that the

RUSLE has overestimated the hillslope erosion values in its sub basins, however field observations suggest otherwise. Site observations in chapter 4.3.6 show that mass bank erosion has occurred in Turpentine Creek. Although the causes for the lack of regular flow in the region are unknown, it is likely that the Curramore sub catchment is heavily affected by extreme conditions such as flood scale rainfall events. Additionally, it should be noted that the RUSLE is not an event-based model, rather it predicts long term erosion trends. For this region an event-based assessment using a model such as OzMUSLE, may more appropriately represent the erosion characteristics of this area (Simms 2007).

6.5 Recommendations

6.5.1 Model improvements

The RUSLE model used in this report provides a best estimate of long-term erosion trends occurring in the Minnamurra river catchment. The accuracy of the RUSLE model is limited by available data both for use in creating the C and K factors of the model, as well as validation data such as sediment yield measurements aided by Ceasium-137 and/or Lead-210dating. An improved LiDAR program could be investigated to address the incomplete catchment DEM at resolutions >30m, which would improve the RUSLE final values by eliminating the effects of edge contamination (see chapter 4.1.2). Installing stream gauges that can measure TSS and flow rates would be beneficial in monitoring the catchment, especially during rainfall events. This would provide further validation to the RUSLE model, and it could be used to aid management if a tributary were to exceed a trigger value. Additionally, access to consistent data provided by gauges would allow more complex models such as SWAT and Sednet to be applied to the catchment. This would provide more effective forecasting and a more customisable interface if changes such as new infrastructure is planned to be added in the catchment.

6.5.2 Catchment Management Recommendations

The RUSLE and the field measurements of this study should be referenced to aid in management assessments of the catchment. The estimations of hillslope erosion by the RUSLE model indicate that high erosion to a magnitude >10ton/ha/yr occurs in the Turpentine and Curramore sub basin. It is advisable that this region is given management attention regarding improvements in hillslope vegetation, in order to provide adequate erosion protection. The bank erosion site referred to under heading 4.3.6 is one area in need of remediation as they gully type feature is likely to worsen if left unattended. This recommendation extends to basins such as Hyams, Fountaindale and Jerrara where landcover is similarly patchy.

Due to the lack of validation accessed in this study for the Curramore and Turpentine basin as a result of poor flows, studies could be set up to investigate the region. This could include landowner surveys which focus on their experience with erosion on their land and if they think the issue is significant enough for a follow up study. The upper catchment, which was originally set to be the focus of this study showed very low incidences of erosion and sediment movement through the upper river, Frys Creek and Burra Creek. Therefore, it is suggested that these areas are maintained in their current state in order to preserve this. Field sampling revealed that the water quality in Fountaindale Creek is anomalous when compared with the mid-range erosion, TSS and nutrient values estimated for the sub basin. This suggests that there are localised factors that should be followed up if further analysis results in similarly high values. These factors could include bank trampling by cattle and poor riparian vegetation that could be improved. Preventing cattle access to the riverbanks would also improve water quality and reduce sediment loads in tributaries. This would supplement riparian revegetation programs, as cattle setbacks would prevent the damage of emergent plants by grazers.

7 Conclusion: Usefulness of RUSLE for informing management

The aim of this study was to identify the erosion patterns of the Minnamurra River catchment and identify sub-basins that require management attention using a GIS modelling approach. The RUSLE model and its accompanying validation have effectively addressed this aim by locating areas in the catchment which are eroding more rapidly than others. It has addressed that the upper catchment is experiencing less erosion than the northern and southern slopes.

For a pilot study such as this, the RUSLE model and field study has functioned effectively to indicate where management goals should be focused. These goals are:

1. The Curramore and Turpentine Creek sub basin
    - Put in place remediation strategies to stabilise the bank indicated in figure 26
    - Improve vegetation cover on hillslope and riverbanks
    - Undertake a landowner survey to understand how erosion in the area is affecting local businesses and residents
2. Fountaindale Creek
    - Improve riparian vegetation cover
    - Advise that bank setbacks should be applied to livestock
    - Conduct follow up samples
3. Low vegetation areas of Hyams and Jerrara Creek basins
    - Improve vegetation cover especially on sloping land

Some goals for Kiama MC could include gauging of tributaries to provide continuous water quality data. The measurements from these gauges could be used to formulate more complex models such as SWAT. These recommendations come as an early attempt to estimate the erosion and sedimentation trends of the upper Minnamurra catchment, filling a knowledge gap that existed.

The RUSLE model provides validated hillslope erosion values but can be improved. Further research would be required to add confidence to the RUSLE values, and the calibration of its factors. Additional study could focus on improving the resolution of the soil erodibility K factor, and an in-depth analysis of changes in the land use C factor using improved aerial photography. A high-resolution LiDAR program that covers the complete catchment would improve LS factor formulation. Although the RUSLE did not predict that the Fountaindale Creek basin was highly erosive, the fieldwork put in place for validation of the model did identify the trend. This shows that although the model has limitations, it still facilitates catchment health assessment beyond the model itself and should be referenced when anomalous results occur during sampling runs.

This project demonstrates the usefulness of the RUSLE in providing catchment erosion estimates that can be used to guide management efforts.

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